# MS Thesis

## Environment and Natural Resources

# Accounting for the Utilisation of Energy Resources within the Genuine Progress Indicator

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HÁSKÓLI ÍSLANDS

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60 ECTS thesis submitted in partial fulfillment of a

*Magister Scientiarum* Degree in Environment and Natural Resources

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## Abstract

This Master's thesis critically examines the Genuine Progress Indicator (GPI), evaluating its robustness as an alternative measure of sustainable economic welfare. It is recognised that the GPI was initiated to mainly reflect strong rather than weak sustainability principles and embrace a Fisherian conception of income and capital. In the light of these two core understandings, this thesis reviews the GPI's accounting methodology for the costs of non-renewable energy resource utilisation. It is argued that the most apt means of applying cost deductions for the utilisation of fossil and nuclear fuels is the full-cost replacement approach, expressed in terms of the present value of the most suitable renewable energy fuel alternative.

Prior to this thesis, neither existing calculation methodologies nor academic reviews of the GPI had considered the importance of maintaining sustainable yields from renewable energy resources. In particular, geothermal resources, although renewable in the sense of the Earth's almost ubiquitous capacity to store heat, are frequently utilised for electricity generation at a rate that is unsustainable. Pressure recovery and fluid-heat recharge periods typically endure for several decades or more. Where geothermal resources are utilised unsustainably, this thesis contends that the GPI should deduct costs for the excess depletion of 'renewable' energy resources. This approach would maintain the GPI's methodological correctness as a measure of sustainable economic welfare in current time terms. Failure to do so is affirmative of the weak sustainability paradigm, inferring that overexploited energy resources can be either fully replaced or partially substituted when their yields begin to diminish.

This thesis draws upon the example of Iceland to delineate a new method for calculating a GPI cost deduction for the unsustainable utilisation of geothermal resources. The advised approach synthesises existing academic theory concerning the sustainable utilisation of geothermal resources and levelised energy cost calculations.

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# 1 Introduction

## 1.1 Introduction to Economic Welfare and the Genuine Progress Indicator

In the field of economics, economic welfare refers to the sum of utility gained through the consumption of material goods and services (Weisbrod and Hansen, 1968). It is the component of social welfare that is fulfilled via economic activity and is usually measured through Gross Domestic Product (GDP). However, in reality, economic welfare is derived from many more aspects than can be captured via the aggregation of national economic activity. Nor does GDP provide any indication of the sustainable nature of economic activity. Whether the basis of economic activity is predominantly finite non-renewable resources or renewable energy, GDP alone is unable to communicate the difference to policymakers. Simplicity is the undoing of GDP, although it was never intended to represent the omnipotent measure of economic welfare which it has ultimately become.

In contrast, the Genuine Progress Indicator (GPI) is a comprehensive measure of sustainable economic welfare, and is designed to take full account of many environmental and social factors which are overlooked by the GDP statistic. Whereas GDP accrues on a twofold scale when pollution occurs (via the economic act itself causing pollution and the following costs of clean-up), the GPI methodology counts this damage as a cost deduction roughly equivalent to the monetary value of the clean-up activity (Bagstad and Shammin, 2012). The GPI is an attempt to measure whether the environmental impact of the products produced and consumed in a country currently represents a negative or positive contribution to economic welfare, and the extent to which such activity is sustainable into the future. GPI advocates claim that it can more reliably track economic progress by assimilating the ecological impacts of production into the equation (Costanza et al., 2009).

The GPI methodology has emerged within the field of ecological economics, a modern movement which places emphasis on 'strong sustainability' values, those rejecting the idea that natural and human forms of capital are substitutes for one another (Neumayer, 2004). The concept of welfare in ecological economics is differentiated from understandings of the term generally voiced by neoclassical economists. Often ecological economists opine that neoclassical economists ignore the environment, viewing it as a subset of the human economy (Bartelmus, 2010; Vatn, 2010). The field of ecological economics distinguishes itself from neoclassical interpretations of the value of nature by reinforcing the observation of economies embedded within environmental systems. Thus, it is important to distinguish between two economic paradigms: one which considers the environment as a constraint within a holistic system, the other maintaining that it represents a pot of resources to be fully utilised to serve the human economy. The GPI has emerged from the former school of thought, factoring in deductions for economic activities that result in welfare depletion such as inequality, pollution, environmental damage and non-renewable resource utilisation.

## 1.2 Energy and Non-Renewable Resource Depletion

### 1.2.1 Energy Consumption and GDP

Energy is integral to the flourishing capacities of all life. Every activity on Earth is dependent on energy and economies cannot be sustained without energy inputs. However, the intensive use of energy, particularly when sourced from non-renewable resources, is also the cause of a number of environmental and societal ills to the detriment of economic and social welfare. Energy production and consumption activities have been linked to local health impacts, global climate change, air and water pollution, soil contamination, biodiversity loss, resource depletion, security implications and land-use conflicts (Johansson and Goldemberg, 2002; Bagstad and Shammin, 2012). Even in the face of such effects, the attention of government policymakers and corporate interests tends to be focused on the continued deployment of non-renewable energy resources rather than renewable energy alternatives.

Nations that consume more energy than others tend to have higher GDP, although the causality in this relationship remains subject to scrutiny (Ozturk and Acaravci, 2010). GDP fails to acknowledge that the faster non-renewable resources are depleted to provide energy to fuel economic activity, the more pollutants that are likely to be emitted. National accounting measures count the loss of natural capital resources and their many non-market services as an economic gain. Repetto and Austin (1997, p.61) describe the problem as "a country could exhaust its mineral resources, cut down its forests, erode its soils, pollute its aquifers and hunt its wildlife and fisheries to extinction, but measured income would not be affected as these assets disappeared". Viewed collectively, these effects carry implications for human health, social well-being and the sustainability of economic welfare itself. As Chapter 2 of this thesis will outline, the GPI strives to incorporate the variety of environmental, social and economic implications that result from the consumption of non-renewable energy resources. Thus the GPI deducts costs for issues such as non-renewable resource depletion, ozone depletion, air pollution, water pollution. A global reliance on non-renewable sources has led to calls for a 'sustainable energy system' (Geller, 2002), and this thesis will contend that the current suite of cost deductions from the GPI is often an insufficient means of expressing this vision and the 'strong sustainability' paradigm that the measure seeks to reflect.

### 1.2.2 Sustainability and the Sustainability of Energy Use

For the purposes of this thesis, the terms *sustainability and sustainable development* will be used interchangeably. Sustainable development was defined by the Bruntland Commission as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (Bruntland, 1987, p.43). This definition encourages a reduction in the negative environmental, social and economic impacts stemming from development processes, while economic welfare continues to flourish.

Bearing in mind the constraint of finite non-renewable resource stocks and various impacts deriving from their utilisation, sustainable energy can be described as an energy system that provides "adequate energy services for satisfying basic human needs, improving social welfare and achieving economic development throughout the world without endangering the quality of life of current and future generations of humans or other species" (Geller, 2002, p.16). This definition is also commensurate with other interpretations of the term sustainable energy, which emphasise the importance of utilising replenishing resources and minimised waste streams that do not exceed the absorptive capacity of the environment (Tester, 2005). In general, the components of a sustainable energy system include the following:

- Reduced demand for and dependence on conventional energy supplies (fossil fuels and nuclear energy) through changes in consumption patterns, including changes in behaviour and the more efficient use of energy;
- Using cleaner sources of conventional energy, such as natural gas, as a bridging fuel and developing ways to reduce the impact of more polluting sources;
- A much greater reliance on renewable sources of energy;
- Ensuring accessibility to adequate energy services at reasonable cost for all sectors of the population in the most environmentally sustainable ways (Lipp and Cain, 2007)

Over the longer term, the potential for increased non-renewable resource scarcity represents an important reason for shifting towards a sustainable energy system on a global scale. The issue of remaining recoverable non-renewable resource stocks splits opinion with optimistic perspectives (Greene et al., 2006) countered by more pessimistic views (Chopra, 2011). The GPI rewards nations that increase their use of renewable energy – a relative increase in sustainable economic welfare is derived from a lower cost deduction for replacing utilised non-renewable resources with renewable alternatives. This is logical, not least because greater use of renewable energy leads to the less rapid depletion of scarce non-renewable resource stocks and the point of absolute depletion is shifted into the future (Kruyt et al., 2009). In addition, other 'negative externality' cost deductions within the GPI associated with fossil fuel and nuclear combustion are ameliorated.

Renewable energy forms are those obtained from the continuous or repetitive currents of energy recurring in the natural environment, and as such cannot be depleted (Twidell and Weir, 2003). Energy sourced from solar, wind and tidal sources are the ultimate forms of renewable energy due to their constant replenishment (Lipp and Cain, 2005). Another source of energy commonly considered to be renewable is geothermal (Menagaki, 2011; Manzano-Agugliaro et al., 2013). However, geothermal energy may not necessarily be renewable as this depiction depends on site-specific heat extraction and replenishment rates. The maintenance of sustainable yields from geothermal power is greatly limited by the speed at which heat travels through solid rock (MacKay, 2008). After a certain time period, the process of extracting heat for utilisation in a geothermal power station may deplete the energy resource, at least temporarily. If unsustainable rates of extraction occur, the geothermal resource ceases to be renewable or a valid component of a sustainable energy system. Indeed, the geothermal resource should instead be considered to be non-renewable, one not renewing itself at a sufficient rate for sustainable economic extraction.

The GPI – to reiterate – is a measure of sustainable economic welfare. Cost deductions are incorporated for the utilisation of non-renewable resource stocks, such as fossil fuels or uranium. However, a default assumption is embedded within this component of the GPI: the use of alternative energy sources to fossil fuels and uranium equates to a greater level of sustainable economic welfare. Evidently, when utilisation rates are too high for resources commonly considered as being renewable, then at least a proportion of these 'renewable' energy sources should be considered as though they are non-renewable stocks. Furthermore, the GPI has been designed by ecological economists to reflect strong sustainability principles, even if in practice it demonstrates predominantly the weak sustainability paradigm. The utilisation of renewable energy accords with the strong sustainability school of thought, but only when natural capital resources are depleted at rates that do not reduce the potential for future harvest. Where this is not the case, substitutability in the form of replacement renewable energy assets is required to replace the generation shortfall, and the cost deduction applied in the GPI for non-renewable resource utilisation should be correspondingly higher.

## 1.3 Aims and Objectives

This Master's degree thesis will examine the GPI, evaluating its general effectiveness as a measure of sustainable economic welfare, and propose a revised method for calculating deductions for the utilisation of finite non-renewable resources. A higher GPI outcome (all other factors being equal) can be attained by a country shifting its pattern of energy supply from non-renewable fossil fuels to renewable energy sources. The deduction ascribed to non-renewable resource utilisation has commonly been calculated as the replacement cost of renewable energy resources, and in the United

States this is considered to be the amount of investment in biofuel needed to replace the loss of fossil fuels (Griffiths et al., 2009). However, this approach overlooks the fact that taking purely a cost deduction for non-renewable resource depletion assumes that the alternative option – the use of more renewable energy – generates a stream of sustainable consumption opportunities. As the GPI strives to measure sustainable economic welfare, it should not only include deductions for the loss of finite non-renewable resources, but also the over-exploitation of certain renewable energy resources.

This thesis intends to answer in chronological order the following research questions:

1. To what extent do alternative measures of economic welfare to GDP demonstrate accordance with the strong or weak sustainability paradigms?
2. How should the GPI's methodology best account for costs pertaining to non-renewable resource depletion?
3. What is an appropriate method of integrating costs for the unsustainable utilisation of geothermal energy resources into the GPI's methodology?

This thesis will explore the case study of Iceland, a country that sources almost 100% of its electricity supply from renewable energy resources in the form of hydro and geothermal power (Aslani et al., 2013). However, existing national GPI methodologies would not apply a cost deduction for the unsustainable utilisation of such resources. Indeed, Iceland's geothermal resources are widely considered to be renewable, but have been shown to be either temporarily or permanently incapable of delivering a sustained yield (Ketilsson et al., 2010). The Icelandic GPI, which has not yet been published, would vary from many other countries in the world due to its widespread utilisation of abundant renewable energy resources. In contrast to other national GPI studies, the calculation of the GPI statistic for Iceland would not include a significant deduction for the exploitation of non-renewable resources. For nearly all of the other countries where the GPI has been calculated, the subtraction of non-renewable energy resources represents the largest deduction in the GPI account (Wilson and Tyedmers, 2013). However, this thesis will demonstrate that an increased cost deduction should apply when renewable resources are utilised unsustainably.

No academic studies have been carried out to evaluate how best to incorporate the sustainability of renewable energy use within the GPI methodology. This thesis is therefore a means of establishing a methodological improvement to the GPI, resulting in a more precise approximation of sustainable economic welfare. The observations and improvements will have some international significance, as a measure of the sustainable utilisation of geothermal energy resources should be incorporated within calculations of the GPI.

## 1.4 Thesis Structure and Methodology

The structure for the three main substantive chapters in this thesis is set out below and has been established to provide a thorough, coherent and informed response to the three research questions. A discussion section (Chapter 5) then considers the main implications, constraints and practical limitations of the recommended accounting methodology for the costs of non-renewable and unsustainable 'renewable' resource depletion.

### 1.4.1 Chapter Two – Literature Review

This chapter begins by deepening the introductory analysis of measures of sustainable economic welfare, beginning with a literature review which evaluates the nature of GDP and then considers the merits of a range of various alternatives: Net Domestic Product (NDP), Measure of Economic Welfare (MEW), Sustainable Measure of Economic Welfare (SMEW), Environmentally Adjusted Domestic Product (EADP), Genuine Savings Index (GSI), Sustainable National Income (SNI), Index of Sustainable Economic Welfare (ISEW) and the GPI.

The analysis is carried out in the light of a detailed appraisal of the existing literature concerning the strong and weak sustainability paradigms, exploring concepts such as the Hartwick Rule and Fisherian notion of 'psychic income', while maintaining a focus on key issues such as the substitutability of capital, functions of natural capital, importance of stimulating a transition from the use of non-renewable to renewable resources, and the influence of intergenerational ethics. In so doing, this approach is able to reveal the evolution of alternative measures of economic welfare, as well as providing a detailed response to the first research question considered in this thesis. During this analysis, it is recognised that the GPI is not a measure of environmental sustainability as such, and rather it is an approximation of the sustainability of economic welfare. Therefore, the most robust of the alternative measures incorporate environmental costs as welfare deductions, but they cannot assimilate the many environmental threshold and waste assimilative constraints needed to be considered when appraising environmental sustainability per se.

### 1.4.2 Chapter Three – Accounting for Non-Renewable Energy Resources

This chapter provides a detailed response to the second research question – what is the most appropriate means of deducting costs from GPI for non-renewable resource utilisation? Continuing from the themes espoused in Chapter 2, strong sustainability arguments are used to justify the use of a full replacement cost approach in contrast to methods which deduct only a fraction of the costs, such as the resource rent and 'El Serafy' user cost methodologies. These alternative approaches are considered to be reflective of the weak sustainability paradigm, and their use in cost deduction calculations undermines the credibility of the GPI, which is founded upon strong sustainability principles, even if its final statistic is reflective of a level of substitutability between capital classes. Although the replacement cost approach has been widely applied, particularly within the United States and United Kingdom GPI's, this thesis contends that its assumption of rising renewable energy prices is flawed. On the contrary, it is more appropriate to deflate future renewable energy prices on the basis of their wider diffusion and long-run economies of scale benefits.

This thesis considers a range of possible approaches to valuing non-renewable resource depletion, but reinforces the need to consider the best renewable fuel alternative in the light of specific criteria relevant to the assessment locality.

### 1.4.3 Chapter Four – Accounting for the Utilisation of Renewable Energy Resources

Chapter 4 contemplates the third research question concerning the need for the GPI to incorporate costs when the production of renewable energy cannot be sustained. Initially the chapter defines and discusses the concepts of energy sustainability and renewable energy. The GPI incorporates many of the aspects of energy sustainability, but is somewhat deficient in terms of its interpretation of long-term security of supply issues. Indeed, along with many academic texts, national GPI studies have thus far assumed all renewable energy technologies to demonstrate sustainable yields of supply (or sustainable utilisation). This is not the case. Drawing upon the most prominent example of geothermal resources, which typically have very slow rates of pressure and heat replenishment, Chapter 4 examines different modes of production and sets out a proposed methodology for calculating GPI cost deductions for the unsustainable utilisation of 'renewable' resources. The proposed methodology builds on case study examples and integrates strong sustainability thinking, welfare economics, and the current model for the sustainable utilisation of geothermal resources proposed by Axelsson (2010). Using a number of assumptions in the absence of concrete data, Chapter 4 concludes by estimating the potential GPI cost deductions for utilised energy resources in Iceland.

# 2 Literature Review

## 2.1 Economic Growth as a Flawed Measure of Human Economic Welfare

## 2.2 Introduction to GDP

GDP is a measure of economic activity within a nation, expressing the monetary market value of all final goods and services produced in a country over the course of a year (Bergh, 2009). It comprises the monetary sum of domestic consumption, investment, spending by government and net exports (Lipsey and Harbury, 1992). In its simplest form, GDP measures the annual sum of a circular flow of expenditures and income within a national economy (Lipsey and Harbury, 1992). Figure 2.1 depicts a straight-forward representation of the traditional circular flow model of national economies.

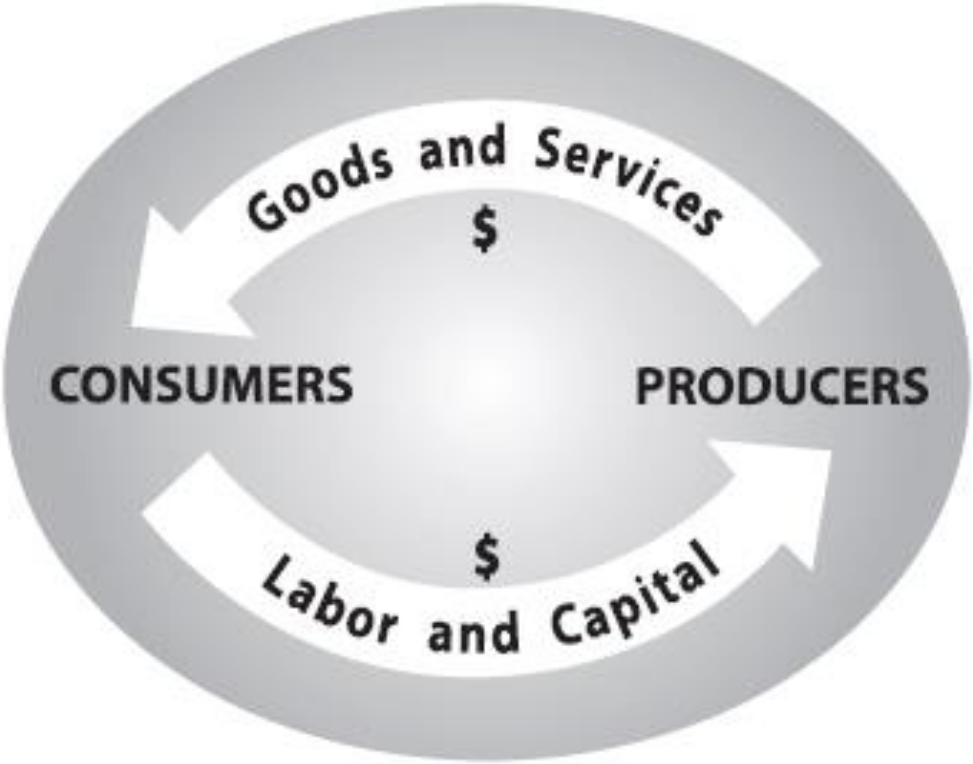


**Figure 2.1: Traditional Circular Flow Model of the Economy (Hart, 2000)**

In the circular flow model of the economy, the production of goods and services by business firms lead to incomes for householders. Most of this income will consist of wages, with the remainder paid out in royalties, rent and interest. The sum of income received by consumers then represents the financial means necessary for consumption and investment in producing firms. In reality, the circular flow model is complicated by a series of leakages (for example, saving) and investments (for example, government spending) into the system and the role of the financial sector (Harris and Codur, 2004), but this simplified model gleans an insight into the nature of economic processes and how they relate to GDP, a statistic that effectively represents the annual 'electricity meter' of combined activity.

Although economists have focused upon the three factors of production that form a backdrop to GDP – land, labour and capital – it is only in recent years that the issue of natural capital has been allocated a specific focus. Harris and Codur (2004) draw upon the term 'natural capital' as referring to all of the natural resources necessary to facilitate economic activities. An expanded viewpoint of the GDP calculation methodology is necessary in order to deduce two key observations: (1) natural processes provide essential support systems to human economic (and overall) welfare and need to be accounted for, and (2) recognition that support for GDP depends on resource availability constraints, and thus there are limits in terms of the resources that can be extracted from the planet and its biosphere (Daly, 1987).

### 2.2.1 GDP and Growth as a Measure of Economic Welfare

The methodology for quantifying GDP and the System of National Accounts (SNA) arose during the 1930s and 1940s, a time when the world was at war for the second time, and still recovering from the Great Depression. By the early 1940s, the United States (US) was beginning to emerge out of recession, however their anticipated and economically costly involvement in World War II led to concerns that the standard of life for American citizens would soon diminish (Landefeld et al., 2008). Marcuss and Kane (2007) discuss how President Roosevelt used GDP estimates to show that the economy could not only provide sufficient support for fighting in a global conflict, but also facilitate sufficient support for the production of consumer goods and services.

The use of GDP as a measure of economic progress was further enhanced as a consequence of the Bretton Woods Conference in 1944. As Costanza et al. (2009) pontificate, economic instability across many nations had been a major causal factor in the outbreak of World War II, and resolving this situation required stable currency exchange rates and the removal of barriers preventing international trade. The Bretton

Woods Conference strived to accelerate economic progress and recovery as a means of promoting peaceful international relations. Improving economic welfare was viewed as being the instigator of world peace, and a pathway of growth would lead to improved human welfare overall. Key outcomes heralding from the Bretton Woods Conference were the creation of the International Monetary Fund (IMF) and the World Bank. These were US-led institutions, at least initially, and the work done by the US in developing the GDP methodology for monitoring economic performance had informed much of the Bretton Woods debate (Eichengreen and Kenen, 1994). As a result, GDP became the main means via which the IMF and World Bank measured economic progress, despite a restructuring of these organisations in the 1970s, leading to a less-dominant role for the US (Irwin, 1996).

Despite warnings by many economists over the last 70 years, GDP growth continues to be used as an indicator of increased economic welfare (Jones and Klenow, 2010). Per capita GDP growth is often used to assess quality of life differentials between countries (Bergh, 2009). According to McCulla and Smith (2007, p.1), GDP remains “one of the most comprehensive and closely watched economic statistics: it is used by the White House and Congress to prepare the Federal Budget, by the Federal Reserve to formulate monetary policy, by Wall Street as indicator of economic activity, and by the business community to prepare forecasts of economic performance that provide the basis for production, investment, and employment planning”. Costanza et al. (2009) form the view that GDP and economic growth are terms used as though they measure human and societal progress itself, a view strengthened in the light of a report from the World Bank which stressed that only long-term and high rates of GDP growth (specifically, a doubling of GDP each decade) can solve the world‘s poverty problem (Commission on Growth and Development, 2008).

### 2.2.2 Weaknesses in Using GDP as a Measure of Economic Welfare

A wide-ranging body of research now exists denouncing the merits of using growth in GDP as a yardstick of economic welfare progress. As long ago as 1934, the instigator of the SNA in the United States, Simon Kuznets, advised against marrying GDP growth performance and economic welfare (Costanza et al., 2009). In more recent times, the US Bureau of Economic Analysis assert that GDP performance should be used to provide answers to the following questions: how fast is the economy growing; what is the pattern of spending on goods and services; and how much of the income produced is being used for consumption as opposed to investment or savings (McCulla and Smith, 2007). In other words, all questions related to the total sum of economic activity and its component structure.

However, as Kuznets (1934) observes, GDP does not even account for the total sum of economic activity within a nation. He asserted that GDP should by design be a specialised tool, ignoring earnings from the "services of housewives and other members of the family", "relief and charity", "services of owned durable goods", "earnings from odd jobs", and "earnings from illegal pursuits" (Kuznets, 1934, p. 3-5). Costanza et al. (2009) also note that GDP is almost entirely a measure of national market-based production, albeit it includes some non-market aspects such as 'defensive' government spending on the military, health care and social housing. Indeed, many important economic activities are specifically excluded from the GDP calculation, including volunteer work, social formation, the costs of crime and an increasing prison population, and the depletion of natural resources (Costanza et al., 2009). Stockhammer et al. (1997) consider the nature of GDP and its inclusion of predominantly the type and level of economic activity that is allocated by markets. They conclude that it ignores the following features integral to human economic welfare:

- Many aspects of non-market production;
- Various parts of production that are not disposable for consumption, but are needed to repair damage caused by the economic system itself (defensive costs);
- Environmental damage that is not repaired;
- The reduction of future welfare that is caused by production / consumption today;
- The effort required to attain a certain level of economic welfare e.g. the duration and intensity of the work;
- The imposition of income inequality.

Bergh (2009) comments that the use of natural resources and identification of necessary constraints is entirely overlooked by the traditional circular flow model of national economies. Highlighting the example of pollution to air and marine environments due to economic activities, Bergh (2009) observes that the damage itself does not enter GDP, but the costs of cleaning up the pollution will be included. Furthermore, Stern et al. (1996) state that the capital depreciation associated with environmental change (for example, the loss of fish stocks, biodiversity and forests) and the depletion of resources (for example, fossil fuels and precious metals) is omitted from the GDP calculation. Due to the absence of environmental deductions, the GDP calculation is likely to suggest that a society is much richer in economic welfare terms than it actually is.

In the light of the market and non-market based flaws in the GDP calculation, Hart (2000) portrays in Figure 2.2 a more complete model of the circular flow economy, one inclusive of the social and environmental systems that support economic output and welfare.

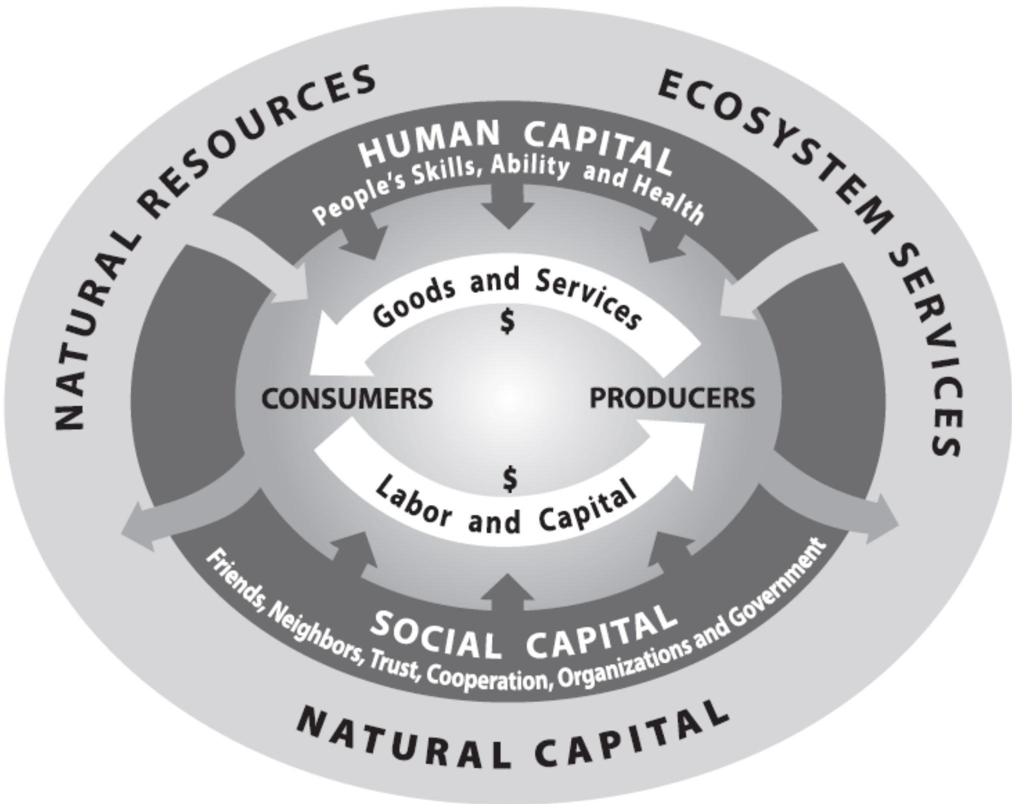


**Figure 2.2: A National Economy and Systems of Support (Hart, 2000)**

Following on from Harris and Codur's (2004) observation that the GDP calculation excludes the concept of resource constraints, Costanza et al. (2009) assert that the methodology encourages the depletion of natural resources faster than they can be renewed. GDP actually encourages the depletion of resources for economic gain, as, for example, the marketed sales of timber from a felled forest far exceed the zero market values ascribed to its ecosystem services, such as water filtration and flood protection (Sagoff, 2011). This situation presents problems in terms of the non-monetary but valuable ecosystem services that are provided to humans for free and support economic welfare. Although quantifying the value of global ecosystem services in monetary terms is fraught with complexities, a study by Costanza et al. (1997) uncovered a speculative value of $33 trillion, more than world GDP at the time.

There are also further concerns about using GDP as a measure of progress due to 'threshold effects'. Studies have shown that as GDP increases, quality of life also follows an upward trend – but only up to a certain point (Greenwood and Holt, 2010). Thus, although economic growth has remained one of the most important targets set by governments, arguments against raising the material standard of living have emerged. Studies by Easterlin (1973; 2005) have examined the relationship between GDP across and within nations over time. In all of these assessments, Easterlin finds that there is no link between the level of economic development of a society and the overall happiness of its members. What does appear to matter in terms of happiness is relative income – those people within countries that have more income are typically happier (Easterlin, 1973). An explanation for this assertion is provided by Layard (2005). He comments that "people are concerned about their relative income and not simply about its absolute level. They want to keep up with the Joneses or if possible outdo them" (Layard, 2005, p.45). However, absolute income does appear to relate to subjective levels of economic welfare for some people, but only those who have a very low income. Layard (2005) discovered that once a nation has a GDP of greater than $15,000 per capita, its level of subjective economic welfare is independent of its GDP per capita (Layard, 2003).

In recent years, detailed studies have been supportive of the 'Easterlin Paradox'. After a certain point, almost every country witnesses a breakdown in the correlation between average absolute income and subjective well-being, as increases in GDP are offset by many private and social costs, including greater income inequality, loss of leisure time and natural capital depletion (Cobb et al., 1995; Wilkinson et al., 2011). Wilkinson et al. (2011) discuss how the pursuit of GDP growth can lead to spiralling income disparity and an array of related social features that are ultimately detrimental to the economy itself – increased crime, reduced worker productivity and reduced investment featuring among the list.

If absolute income has no significant impact on happiness after a certain level has been breached, then there are significant implications for the formation of government policy. Rather than maximising economic growth as the means by which increases in subjective well-being are facilitated, as has been the case since World War II, the emerging academic literature suggests that the primary government policy should instead be focused on directly maximising subjective well-being. The setting of such a target does not preclude the use of economic instruments to promote welfare gains. However, in contrast to the current focus on growth and driving the circular flow of economic activity, policies for the promotion of sustainable economic welfare are more likely to focus on the maintenance of high levels of employment, minimum wage enforcement and delivering low levels of income inequality. In particular, Layard (2005) observes that relative income comparisons imply that each individual's labour effort can impose negative externalities on others due to the shifting of reference points. On this basis, Layard argues, there is a justification for governments imposing higher taxes on income to reduce inequality.

## 2.3 Alternative Measures of Economic Welfare

### 2.3.1 The Nature of Alternative Measures of Economic Welfare

GDP provides a means of quantifying national production for which a monetary income has been received. As McCulla and Smith (2007) note, its use as an income or production measure is helpful for governance institutions when forming macro-economic policy goals for economic output, price level changes and employment. Considerable criticism has been directed at the GDP calculation due to its emphasis on the quantity of goods and services produced, rather than the impacts on economic welfare. It is an ill-equipped and proxy means of measuring human progress and economic welfare, yet political processes have resulted in its widespread use for this purpose for over 70 years.

Over the last twenty years, concern has been raised in relation to long-term rates of natural resource depletion and environmental degradation. Proponents of alternative measures of economic welfare, which do incorporate wider quality of life considerations, generally consider the incorporation of an array of additions to and deductions from GDP (McKenzie, 1983; Costanza et al., 2009). The traditional SNA entirely fails to record the depletion of natural capital stocks as a cost in the production account. At the core of 'green' national accounting approaches is the notion of netting out from investment in new durable capital goods the drawdown in items of natural capital (Asheim and Hartwick, 2011).

### 2.3.2 Weak Versus Strong Sustainability

There remains no single accepted interpretation of the term sustainable development. In accordance with the popular Bruntland definition outlined in Chapter 1 of this thesis, it is widely paraded as 'development that persists over time'. However, such an interpretation lacks depth, failing to satisfactorily reconcile the competing needs of economic development and natural capital retention. Essentially the dilemma considers a single choice: should natural capital be afforded special protection, or can it be substituted by other forms of capital, especially produced capital (Ekins et al., 2003).

Predominantly economic approaches to sustainability frame the dilemma in terms of welfare via the concept of utility and its maximisation. Hamilton (2010) highlights that current income and consumption expenditure data alone is an inadequate measure of economic welfare, and draws upon the work of Samuelson (1961) to support his assertion. Samuelson (1961) argued that economic welfare measures need to integrate present and future consumption expenditure, with the only approximation to a measure of welfare derived from a quantification of wealth-like magnitudes, not income. This idea is broadly akin to Fisher's depiction of current wealth as the present value of future consumption, sourced from three asset types: immovable wealth (land and the fixed structures upon it), movable assets, and human beings (Fisher, 1906). Fisher's main argument was that income is the yield from society's capital stocks, and that income was the flow of services streaming from all human-made products

(Nordhaus, 1995). The total sum of services represented a form of national dividend (Lawn, 2003). Although Fisher referred to the term ‘psychic income’, the term ‘utility satisfaction’ or simply ‘utility’ is more commonly applied by modern economists (Laen, 2003).

Neumayer (2003, p.7) describes a straight-forward intergenerational rule whereby economic development is sustainable “if it does not decrease the capacity to provide non-declining per capita utility for infinity”. Utility can be sourced from four forms of capital: produced, natural, human and social (Dietz and Neumayer, 2007). The creation of wealth is the process of using the four types of capital to give rise to flows of goods and services demanded by consumers, and in so doing maintain or enhance capital stocks (Ekins et al., 2003). If a specific capital stock is not maintained, then at some future point the goods and services derived from it will decrease or cease altogether (Ekins et al., 2003). On this basis, each of the four capital stocks may be linked to a type of sustainability – a denuded natural capital stock is indicative of some level of environmental ‘unsustainability’ (Vitousek et al., 1997). Where different capital stocks are considered to be substitutes for one another, the declining stock of one can be compensated by increases to another (Neumayer, 2003). This is the essence of the weak sustainability concept, whereas strong sustainability advocates argue that both capital classes must be non-declining separately.

The weak sustainability approach initially developed in the 1970s, furnishing neoclassical theories of economic growth with the additional consideration of non-renewable resource extraction as a factor of production (Solow, 1974). Solow (1974) contemplated the optimal use of income generated from the extraction of a non-renewable resource, seeking to establish rules on how to much to consume now and how much to invest in produced capital to increase consumption later. He also posed a third and more underlying question related to whether economic growth could be sustained to allow non-declining economic welfare in perpetuity. Solow (1974) showed that this was very unlikely in a model inclusive of non-renewable resources as factors of production. Instead, he believed that consumption of non-renewable resources converges to zero in the long run, unless very optimistic assumptions were taken about how little an economy is constrained by the finite nature of natural resources.

Due to the finite nature of non-renewable resources, the maintenance of non-declining economic welfare required maintenance of the capital stock, including natural capital. Following on from Solow's work, the 'Hartwick Rule' was developed stating that consumption may be held constant provided that resource rents from non-renewable resource extractions were reinvested in produced capital (Hartwick, 1977). This understanding was eventually generalised into a weak sustainability rule, requiring that total net capital investment (includes deductions for depreciation and capital consumption) cannot be allowed to be persistently negative (Hamilton, 1994).

The weak sustainability paradigm continues to rely on (1) the Hartwick-Solow models of the 1970s; and (2) their assumptions underpinning the imputation of non-renewable and renewable natural resources into a Cobb-Douglas production function. The Cobb-Douglas model was based upon constant and unitary elasticity of substitution between factors of production (Dietz and Neumayer, 2007). Intuitively it can therefore be understood that natural capital and produced capital are considered to be very similar entities, and easily substitutable. Thus in order for the weak sustainability paradigm to be a valid measure of sustainable economic welfare, at least one of the following three statements must be true:

- Natural resources are super-abundant and inexhaustible;
- The elasticity of substitution between produced and natural capital must be greater than or equal to unity;
- Technological progress is able to increase the productivity of the natural capital stock at a greater rate than resource depletion.

In contrast to proponents of weak sustainability, strong sustainability advocates believe that natural capital is to a greater or lesser extent non-substitutable (Kuhlman and Farrington, 2010). In order to comprehend this argument, it is necessary to examine the functions of natural capital. Pearce and Turner (1990) and Ekins et al. (2003) consider four distinct functions of natural capital. Firstly, it provides the raw materials for consumption, production, including food harvests, timber products and non-renewable energy sources. Secondly, natural capital acts as a waste assimilative sink from production and consumption activities. Thirdly, it provides largely intangible amenity services, such as the indefinable visual quality of a landscape. Fourthly, natural capital delivers life-support functions on which human being depend for survival, such as air purification, pollination of crops, and flood mitigation. In contrast to the first three functions, which may permit at least limited substitutability, life support functions are of primary value and "hold everything together" (Turner et al., 1994, p.38).

The strong sustainability approach is grounded in the acknowledgement that some or all of the functions of natural capital – waste assimilation, for example – cannot be replaced by produced capital (Daly and Farley, 2011). Moreover, complex natural systems, such as the global carbon cycle, are only partially understood, and humanity cannot be sure of the damaging effects that might stem from polluting activities. Holling (1973) argued that our lack of scientific knowledge is a precautionary justification for replacing the weak sustainability approach with one focussed on eco-resilience, preserving the functionality of living systems over time and maintaining the stock of each type of capital intact independently. In the most extreme of strong sustainability approaches, no substitution would be permitted, even to provide some produced capital and associated waste assimilation. On a global scale, this view seems to be too strict as eco-resilience is not necessarily achieved via a static view of nature, but could be achieved through a sustainable evolution of natural and human systems (Goodland and Daly, 1996). However, for some of the features determining the healthiness of vital ecosystem services, such a strict approach could be necessary. Life support systems such as food, clean air and a stable climate are almost certainly impossible to substitute (Barbier et al., 1994).

A very strict strong sustainability approach could also be justified where environmental thresholds exist and tipping points are in danger of being breached (Dietz and Neumayer, 2007). Stern and Taylor (2008) highlight the International Panel on Climate Change's imposition of a 450 parts per million ($CO_2$ equivalent) as an example of a strong sustainability approach. This is considered to be the safe threshold at which increases in global temperatures can be kept to between a 2 and 3°C level, and any greater rises will result in effects that cannot be mitigated for by known technological means.

Kahnemann and Tversky (1979) argue for a strong sustainability approach on the basis that the loss of natural capital resources could be irreversible. They also purport the idea that humanity is more averse to losses in utility than gains, and thus we are highly averse to losses in natural capital functions that provide us with utility.

There is also an ethical argument for a certain degree of non-substitutability. Leaving to one side different interpretations of intergenerational ethics, the needs of future societies cannot be satisfied purely in terms of current levels of capital. Of equal importance is the preservation of actual capabilities for self-determination by future generations (Sen, 1999). Using a 'capabilities approach', human welfare is not merely representative of individual utility; instead it implies a value judgement on what is worth achieving, now and into the future.

In order to move the strong sustainability paradigm from philosophy to practice, Goodland and Daly (1996) have advocated specific global management rules:

- The use of non-renewable resources should be reduced as far as possible and replaced with renewable resources;
- Renewable resources should be used such that their stocks do not deteriorate i.e. they are harvested at their maximum sustainable yield;
- The efficiency and recycling of resources should be maximised;
- The environment should be used as a sink for pollution only so far as its natural assimilative capacity does not deteriorate over time.

The current global economic system is reflective of a weak sustainability approach. It relies upon an optimistic assumption that the pursuit of economic growth can be 'decoupled' from material throughput via a decrease in natural resource deployment in production systems, particularly through technological innovation and efficiency gains (Dedeurwaerdere, 2013). Decoupling is thought to lead to a decrease in the consumption of non-renewable resources and generation of waste products needing to be assimilated. Evidence of the decoupling of economic growth from the depletion of natural capital is limited (Jackson, 2011). The last thirty years have demonstrated *relative* decoupling, which is a decrease in the use of natural capital per unit of GDP

(Laurent, 2011). However, in *absolute* terms, the global use of natural capital resources continues to increase (Dedeurwaerdere, 2013).

The relative decoupling of economic output from rates of non-renewable resource consumption is a necessary pre-condition for ecological sustainability (Dedeurwaerdere, 2013). However, even in relative terms, it is an insufficient condition for ecological sustainability as increases in eco-efficiency gloss over vast disparities in performance between developed and undeveloped countries (Jackson, 2011). What is critical for ecological sustainability is absolute decoupling – an actual decrease in the amount of global natural resources consumed. In reality, global energy consumption and carbon dioxide emissions have continued to increase. Jackson (2011) estimates that although the relative efficiency of energy use increased by up to 50% in some OECD countries, across even this relatively wealthy group of nations, absolute energy consumption either increased or remained at the same level.

For current economies which are focused upon achieving GDP growth, the rate of eco-efficiency improvement must be sufficient to offset the growth in population and growth in income spent on goods (Weaver, 2011). Furthermore, (Dedeurwaerdere, 2013, p.21) argues that "eco-efficiency gains need to be 'captured' and dedicated' to reducing the absolute use of resources by the global economy, rather than being redeployed to support further material growth." The global economy, dominated by a weak sustainability approach and assuming substitutability between natural and produced capital, currently ensures that gains in efficiency are directed towards driving consumer demand, necessitating further inputs from natural capital stocks and ignoring intrinsic environmental limits.

### 2.3.3 A Review of Alternative Economic Welfare Measures to GDP

What is understood by the term 'sustainable economic welfare' is evidently difficult to delineate, but it is in part a shifting in focus from maintaining the capacity to provide non-declining welfare in the future (sourced from capital stocks) to maintaining non-declining welfare in the present (Dietz and Neumayer, 2007). Economic welfare can easily be thought of as the total national utility of private consumers in an economy (Dietz and Neumayer, 2007). In this context, what is meant by the term 'sustainability' is even harder to assimilate. Although measures such as the ISEW and GPI may have been designed to reflect the strong sustainability paradigm in terms of their cost deductions, their in-built assumption that the components of total national utility can be added together is undoubtedly reflective of the weak sustainability approach (Dietz and Neumayer, 2007). In arriving at a single end figure, such measures assume that increases to one component (for example, private consumption) can compensate for decreases in another (for example, the costs of environmental degradation). It is also important to note that the ISEW and GPI measures are not quantifying sustainability per se, and in order to do so, their final end figures need to be supplemented with additional biophysical indicators, such as natural capital accounts or the Ecological Footprint Index (Lawn, 2013).

The following sections (2.3.3.1 to 2.3.3.7) discuss an array of alternative economic measures of welfare, all of which are more comprehensive in scope than GDP, although earlier measures tend to omit notions about the finite nature of non-renewable resources. In chronological order, the alternative measures are the Net Domestic Product (NDP), Measure of Economic Welfare (MEW), Sustainable Measure of Economic Welfare (SMEW), Environmentally Adjusted Domestic Product (EADP), Genuine Savings Index (GSI), Sustainable National Income (SNI), Index of Sustainable Economic Welfare (ISEW), and finally the GPI. The particular focus of this analysis is the extent to which each measure adheres to either the weak or strong sustainability schools of thought.

#### *2.3.3.1 NDP*

NDP is the simplest alternative metric to GDP, incorporating deductions for the depreciation of produced assets, such as buildings and machinery. NDP is calculated as GDP minus the amount of GDP needed to invest in replacement productive assets sufficient to maintain the current existing stock (Asheim, 2007). NDP may provide a more rounded assessment of national economic performance, although Pearce and Atkinson (1995) contend that it needs to be extended to include resource depletion components to represent a more accurate metric of human economic welfare. Otherwise it remains a measure entirely reflective of the weak sustainability paradigm.

Estimates of NDP can be derived from the formula:

$$\textbf{NDP} = \textbf{GDP} - \textbf{D}_\textbf{m}$$

*Where $D_m$ is equal to the annual depreciation of existing fixed capital*

#### *2.3.3.2 MEW and SMEW*

In the light of evident shortcomings concerning the use of GDP as a measure of human economic welfare, Nordhaus and Tobin (1972) set about constructing a simple "measure of economic welfare" to establish the main discrepancies between GDP and economic welfare. The MEW was predominantly a rearrangement of components forming the SNA. Adjustments to GDP fell into three broad categories: (1) reclassification of expenditures as consumption, investment and intermediate; (2) imputation for the services of consumer capital, for leisure, and for the product of household work; and (3) correction for some of the negative impacts of urbanisation (Nordhaus and Tobin, 1972).

The goods and services produced by government are included within final consumption data and in GDP at a value equal to incurred costs (Stiglitz et al., 2009). The first category of MEW adjustments to GDP represents deductions from GDP for aspects that are often considered as instrumental and intermediate rather than final output. In particular, the SNA does not distinguish between government expenditures of goods and services in terms of the three sub-categories of intermediate, consumption and net investment (Nordhaus and Tobin, 1972). According to Nordhaus and Tobin (1972), government expenditure for items such as national defence should be treated as necessary overhead costs of a complex industrial state to avoid overestimating their value in the SNA (Stiglitz et al., 2009).

The MEW commences with private consumption as a reference point, not GDP. This figure is then corrected in two stages. Firstly, a measure of MEW is derived by subtracting from total private consumption a list of items that do not contribute positively to welfare (for example, commuting or legal services) and adding in monetary estimates for activities contributing positively to economic welfare (for example, leisure or voluntary work) (Nordhaus and Tobin, 1973). Secondly, the MEW is converted into a sustainable measure of economic welfare (SMEW), which accounts for changes in total wealth (Stiglitz et al., 2009). The difference between MEW and SMEW is broadly akin to the gap between GDP and GNP in national accounts – the SMEW quantifies the level of MEW that is commensurate with the preservation of the capital stock (Stiglitz et al., 2009).

Nordhaus and Tobin (1973) calculated the SMEW for the United States in the period 1929-1965. They discovered that levels of SMEW were always higher than GNP, mainly due to the contribution of leisure, and the directions of growth in GNP and SMEW were strongly aligned (Shlomowitz, 2009). Although the magnitudes of growth differed, for the period 1929-1965 growth rates for the SMEW were approximately two-thirds of those for GNP (Stiglitz et al., 2009). The conclusion drawn by Nordhaus and Tobin was that the differences were relatively insignificant and standard macro-economic tools of analysis (i.e. GDP or GNP) remained satisfactory guides for policymakers (Stiglitz et al., 2009; Shlomowitz, 2009).

The MEW and SMEW represent purely economic quantifications of human welfare, albeit lacking consideration of the distribution of national income (Stiglitz et al., 2009). Both indicators reflect the weak sustainability paradigm, not encompassing the issue of natural resource depletion, environmental thresholds or the dangers of irreversibility (Shlomowitz, 2009). The costs of negative impacts of urbanisation were the only environmental aspects considered within the MEW and SMEW calculations. Shlomowitz (2009) considers that if Nordhaus and Tobin had included the cost of natural capital depreciation, the MEW for the United States would have been much lower, or perhaps even negative.

#### *2.3.3.3 EADP*

A straight-forward green accounting measure can be derived by incorporating the depreciation of natural capital into the NDP formula. Each year the value of natural capital will almost certainly decrease due to non-renewable resource extraction (Harris and Roach, 2013). The loss in economic value of natural capital resources can be deducted from NDP to arrive at EDP, calculated as follows:

$$\mathbf{EDP = GDP - D_m - D_n}$$

*Where $D_m$ is equal to the annual depreciation of existing fixed capital, and $D_n$ is the depreciation of natural capital*

Hanley (2000) describes three distinct versions of the EDP, each with different approaches to calculating natural capital loss in monetary terms: (1) the EDP deducting the depreciation of natural resources caused by their extraction (as per the formula above); (2) the EDP including subtractions from NDP for the costs necessary to reach the same state of the environment at the end of the calculation period as existed at the beginning; and (3) the EDP subtracting the costs of environmental pressure and destruction, calculated using willingness-to-pay (WTP) methodologies.

Irrespective of the many difficulties in calculating a monetary value for natural capital resources (Azqueta and Sotelsek, 2007), it does not automatically follow that EDP represents a policy signal about the sustainability of economic development. EDP is a measure of *potentially* sustainable income. Its statistic is unable to infer whether EDP can be sustained indefinitely (Bartelmus, 2007).

Munasinghe (1999) considers that a lower EDP than NDP does not automatically communicate to policy makers the decision that should follow. Thus it is of limited relevance even according to a weak sustainability interpretation of the sustainable development concept. Indeed, only under the strictest of strong sustainability approaches, where no substitutability is allowed between natural and produced capital, would a difference between NDP and EDP provide a clear information signal. Nor does comparing the growth rates between GDP and EDP necessarily provide a valuable information flow – for example, if a country has a fixed GDP growth rate, no depreciation of produced assets, and environmental depreciation is constant each year, then EDP will grow faster than GDP (Munasinghe, 1999). However, such an example is ignorant of the importance of critical environmental thresholds essential to the strong sustainability paradigm (Dedeurwaerdere, 2013). It is also ignorant of the need for absolute decoupling discussed earlier by Jackson (2011).

#### *2.3.3.4 GSI*

A comprehensive indicator attempting to measure weak sustainability was initially mooted by Hamilton (1994) and Pearce and Atkinson (1995). They set out the GSI, an adjusted national savings measure accounting for the depletion of natural resources and the environment. The GSI is representative of the weak rather than strong sustainability paradigm as it fails to account for any threshold values associated with the depletion of critical natural capital, establish limits to the substitutability between natural and produced capital stocks, and permits infinite substitutability between natural and produced capital classes (Dietz and Neumayer, 2004). Atkinson et al. (2003) have attempted to address the issue of the non-substitutability of natural capital within the GSI framework, proposing that as non-renewable resources are depleted to critical levels, the shadow price of the asset should rise towards infinity. Although this hints to the scale of value pertaining to natural capital resources, it remains a limited approach. Losses to natural capital still need to be quantified in monetary terms and measured through marginal WTP (Dietz and Neumayer, 2004). This approach is complex for very small, incremental changes in economic welfare, let alone vast differences (Freeman, 2003). As such, the GSI is ill-equipped to address any strong sustainability concerns.

In contrast to GDP, NDP and EDP measures of wealth, the GSI includes human and environmental assessments of wealth alongside an economic assessment (Lin and Hope, 2004). National development is considered to be sustainable if the stock of capital (wealth) is increasing or remaining constant over time. In theory, weak sustainability is demonstrated if the GSI is positive, as more resources are being left behind for future generations (Lin and Hope, 2004). The GSI calculation is as follows:

$$\mathbf{GSI = I_k - D_m + I_h}$$

*Where $I_k$ is net investment in produced capital; $D_m$ is net depreciation of natural capital; $I_h$ is investment in human capital*

If an economy has a GSI value of less than zero at some point, then it cannot be described as weakly sustainable (Pezzey and Toman, 2002). Keeping the GSI above a value of zero is broadly akin to the Hartwick Rule regarding rates of consumption of non-renewable resources and maintenance of non-declining human welfare. In accordance with a weak sustainability understanding of development, Hartwick (1977) considered that an economy could maintain its level of consumption provided that it reinvested all rents from non-renewable resource extraction into produced capital. However, a GSI of greater than zero may still not be a sufficient condition for demonstrating weak sustainability (Dietz and Neumayer, 2004). This is because an adherence to the Hartwick Rule and attainment of a positive GSI value arises over a set time period. Weak sustainability can only be guaranteed if the Hartwick Rule is adhered to over all time periods (Asheim, 2007). An economy that has had a negative GSI in the past and positive GSI now will not be currently extracting non-renewable resources at rates commensurate with weak sustainability (Dietz and Neumayer, 2004).

#### *2.3.3.5 SNI*

Many authors have articulated theories on the subject of a sustainable national income. Hicks (1948) made perhaps the first attempt to define the concept as the maximum value that a person can consume in a period without impoverishing himself. Further contributions flowed from Solow (1974) and Hartwick (1977), both of whom describing how to maintain non-declining economic welfare in the face of diminishing stocks of non-renewable resources. However, even as an indicator of weak sustainability, the Hartwick Rule relies on flawed assumptions regarding the substitutability of natural capital, and it is equally ignorant of non-constant time preferences, technological changes and distortionary taxes (Withagen, 1998). Furthermore, Gerlagh et al. (2002) deride Hartwick's analysis on the grounds of its assumption of a perfectly competitive world without externalities, and perfect foresight as to the future physical, legal and economic mechanisms at large. Partially in response to the flawed depiction of reality described by the Hartwick Rule (issues that have become embedded into weak sustainability measures of national income), Hueting (1980) set out a SNI indicator, a measure reflective of the strong sustainability paradigm and showing the cost of reaching pre-specified strong sustainability standards.

The SNI reflects an absolute preference for the preservation of the natural environment (Hueting, 1980). The SNI measure is reliant upon a maintenance cost approach (UN, 1993) in the sense that the monetary value of environmental degradation and loss of functionality (e.g. as a source of water or freshwater) is considered equal to the costs of conservation (Hueting, 1980). In contrast to the GDP measure and SNA methodology, the SNI's calculation procedure ensures that revenues from resource depletion are not counted as income (Gerlagh et al., 2002), therefore reflecting strong sustainability ideals.

The dependence of an economy on unsustainable natural resource extraction is indicated by the gap between GDP (or NNP) and the SNI (Hueting, 1980). Where the SNI increases at a level less than rates of GDP growth, it is apparent that the economy is expanding unsustainably. Moreover, if the gap widens over time, it is equally evident that economic growth has become ever more reliant upon the increased utilisation of natural capital resources. An increasing gap should act as a signal to policymakers that further endeavours are required to enforced sustainability measures across the economy (Gerlagh et al., 2002), although the precise sectors of the economy to target for further regulation are not necessarily revealed by the measure itself.

Hueting's SNI measure draws a clear distinction between objectively determining sustainability and the sustainable use of environmental functions on the one hand, with society's preferences for such a use on the other (Kuik, 2006). This appraisal of the sustainability concept does not automatically require the conservation of all environmental assets (Gerlagh et al., 2002). Instead, and where an environmental function (for example, energy provision) can be performed by many different environmental assets, substitution between these is permissible in principle (Kuik, 2006). Thus the environmental function of resources for energy production could be delivered by fossil fuels or renewable energy alternatives. Under Hueting's model, the sustainable use of an environmental function can occur via the depletion of natural assets, provided depletion occurs alongside an increase in the stock of substitutable assets.

It should be noted that Hueting assumes that society's preference is for the preservation of environmental functions in perpetuity. Societal preferences are at best poorly understood in the present period and they are certainly very unpredictable into the future. Thus "the SNI identifies a correct measure of national income only if one assumes that society's preferences for the sustainable use of the environment are absolute i.e. independent of their costs" (Kuik, 2006, p.1). The SNI therefore resembles purely a static measure of the maximum national income that could leave environmental functions available, now and into the future, but depending upon the current state of technology (Kuik, 2006). Hueting acknowledges the possibility of relative decoupling and admits that technological progress and eco-efficiency improvements could possibly resolve the inherent tension between economic growth and natural capital degradation (Hueting, 1996).

The SNI further assumes that conditions for the sustainable use of environmental can be assimilated and expressed in the form of threshold standards, such as critical standards for global carbon dioxide concentrations or fisheries stocks. The standards need to be expressed in terms of not allowing more pollution than can be naturally assimilated by the environment, or imposing a total allowable annual catch for fish stocks that does not deplete the stock (Hueting and Reijnders, 1998). As Kuik (2006) discusses, the SNI outcome is dependent on the particular sustainability standards set, as the maintenance cost of damage to environmental functionality is calculated relative to these. Not only is the process of establishing sustainability standards an almost exhaustive process, considerable scientific uncertainty surrounds the accuracy of sustainability standards (Ekins et al., 2003). As such, the SNI is correspondingly also reflective of uncertainty and it is unable to quantify irreversible losses to natural capital.

#### *2.3.3.6 ISEW*

Originally developed by two ecological economists, Daly and Cobb (1989), the ISEW groups together several components of sustainable economic welfare according to three categories: economic, social and environmental (Daly and Cobb, 1989). Brennan (2008) considers the ISEW to rely upon three main theoretical foundations: (1) an 'economics for community' model, which considers the costs and benefits to society rather than individuals; (2) Fisher's concept of 'psychic income' and the services that flow from goods; and (3) the use of social welfare functions. Taking principles from welfare economics, the ISEW combines cost-benefit analysis with social choice theory, its methodology capturing many social concerns about welfare not appropriated by individual interests in the market place.

Instead of combining all national expenditures, as is the case with the GDP calculation, the ISEW is balanced by factors such as income distribution and the costs of environmental degradation and depletion (Jackson et al., 1997). Although a single and internationally agreed calculation methodology for the ISEW does not exist, Brennan (2008, p.1) generalises the ISEW as "adding the monetary service benefits yielded by both the stock of consumer and public durable expenditures (while adjusting personal consumption for income inequality) and household production, minus the environmental and social costs associated with production, distribution and exchange".

The ISEW commences with a basic measure of economic welfare: personal consumption extracted from the SNA. An inequality weighting is applied, and this respects Lawn's (2003) observation that extra money provides greater marginal utility to the poor than the rich. Commencing the ISEW calculation with the aggregate monetary value for consumption expenditure does not in itself indicate that consumption is in itself a positive contributor to sustainable economic welfare (Lawn, 2003). Rather, in accordance with Fisher's 'psychic income' perspective, consumption is viewed as a necessary activity to glean services that can be enjoyed. If an economy is able to facilitate an identical level of service provision but via a decreased level of consumption (perhaps caused by an increase in the efficiency of produced capital), then the ISEW will reflect this as a gain due to a reduction in deductions from consumption, such as the depletion of non-renewable resources (Lawn, 2003). Fisher's (1906) conceptualisation of income and capital implied that the maintenance of produced capital stocks engenders costs, and thus the ISEW also incorporates deductions for losses to the natural capital services sacrificed as throughput for goods. Lawn (2003) maintains that the ISEW establishes consistency with Fisherian concepts of income and capital by deducting the cost of the lost source, sink and vital ecosystem services provided by natural capital. These deductions are as follows:

- Loss of farmland and the cost of resource depletion (source services)
- Costs of ozone depletion and air and water pollution (sink services)

- Costs of long-term environmental damage and loss of wetlands and old-growth forests (ecosystem services)

Where negative externalities arise in society, the ISEW maintains 'collectivism of totalling, socialising the costs' (Brennan, 2008). In other words, the ISEW internalises costs for issues such as pollution and income inequality. Neumayer (1999) considers that the ISEW assumes all personal consumption contributes to economic welfare. As consumption expenditure includes monies spent on drugs, junk food and guns, at least a proportion of its components are not likely to lead to a growth in Fisher's 'psychic income'. Lawn (2003) points out that all economic welfare indices have to make value judgements about what contributes to welfare, and thus this 'weakness' does not undermine the ISEW's legitimacy. Furthermore, some of the negative aspects of undesirable forms of consumption are in fact captured by the ISEW, such as increased healthcare costs and reduced productivity (Dietz and Neumayer, 2007).

The academic literature contains several articles discussing the shortcomings of the ISEW measurement (Lawn, 2003; Lawn, 2005; Dietz and Neumayer, 2007; Beca and Santos, 2010 and Lawn, 2013). Beca and Santos (2010) are particularly concerned with the ISEW's method of accounting for externalities as flows rather than stocks. For instance, the ISEW accounts for the accumulated costs of carbon dioxide emissions on only a flow basis. Although Beca and Santos (2010) agree that this is the least difficult approach, the authors consider that the ISEW should also integrate insights on the stock of carbon dioxide being accumulated in the atmosphere. Nor does the ISEW contemplate the importance of critical environmental thresholds and irreversibility (for example, biodiversity loss) in connection to reductions in natural capital stocks (Lawn, 2013), and Dietz and Neumayer (2007) contend that the methods used in the monetisation of costs to the natural environment are often crude and very inconsistent. By ignoring critical environmental sustainability considerations pertaining to depleted natural capital stocks, there is a danger that these may decline to levels that are ecologically unsustainable. As economic growth largely relies upon the substitutability of natural for produced capital, the ISEW may need to be supplemented with a natural capital account (Lawn, 2003). Lawn (2003) describes an evaluation of this kind in Australia which showed a falling level of economic welfare at the same time as natural capital stocks were becoming increasingly ecologically unsustainable. The use of additional measures in tandem with the ISEW, such as the Ecological Footprint and Bio-Capacity Indices, could help to provide robust evidence as to the environmental sustainability of a nation's economy (Wackernagel et al., 1999).

The policymaking relevance of the ISEW is questionable. The calculations reveals much about economic activities in the present and immediate past, but nothing about the future impact of activities if left unchecked (Lawn, 2013). A supplementary index would again be useful to describe the likely future economic costs and benefits of current actions. The use of additional environmental forecasting techniques could prove valuable, especially if they lead to an 'adjusted' ISEW measure showing the net benefits of moving towards a more sustainable economy (Pezzey and Wiltage, 1998).

The original vision for the ISEW was a reflection of the strong sustainability paradigm (Daly and Cobb, 1989). As strong sustainability requires all capital stocks to be non-declining, the ISEW does not adhere to this vision. The ISEW does not identify different indices for the two main types of capital: produced and natural. Instead, by computing a single overall index, values for produced and natural forms of capital are merged together (Neumayer, 1999). As strong sustainability demands that the stock of natural capital is non-declining, the ISEW is unable to provide a measure for this paradigm. Rather, it is at best a measure of weak sustainability, assuming as it does perfect substitutability between natural and produced forms of capital (Neumayer, 1999).

#### *2.3.3.7 GPI*

During the middle of the 1990s, the ISEW was revised and updated by the Redefining Progress think tank to become the GPI. Although both methodologies are very similar, still in use and endeavouring to measure sustainable economic welfare in monetary terms, the GPI is now more commonly assessed at the national level. To reiterate very briefly on the discussion of the ISEW methodology, the GPI calculation begins with the main constituent of GDP: private consumption expenditure (Posner and Costanza, 2011). In order to reflect the welfare impacts deriving from the distribution of income, personal consumption is weighted according to inequality. The next step is to add or subtract a monetary valuation for activities that either contribute to or diminish economic welfare. Costanza et al. (2004) describe the calculation process as a weighting for income distribution followed by adjustments related to household expenditures and work, mobility, social capital, pollution, land loss, natural capital and net investment. According to Posner and Costanza (2011), the most common basic formula for calculating the GPI is:

$$\mathbf{GPI = C_{adj} + G_{nd} + W - D - E - N}$$

*Where $C_{adj}$ is personal consumption expenditures adjusted for inflation; $G_{nd}$ is non-defensive government expenditures; W is non-market contributions to welfare; D is defensive private expenditures; E is the costs of environmental degradation; and N represents the depreciation of the natural capital base.*

A more detailed description of the GPI calculation is provided by Harris and Roach (2013). Using the method adopted for the United States' GPI calculation, they describe and briefly justify the main steps, particularly via comparison with the approach used to calculate GDP. Their analysis is summarised in Table 2.1 overleaf:

**Table 2.1: Typical Calculation Process for the GPI**

| Stage | Component | Summary Explanation |
|---|---|---|
| 1 | Weighting personal consumption by income inequality | Personal income is adjusted to reflect the degree of income inequality in a society. |
| 2 | Adding in the value of household labour and parenting | GDP includes only paid household and parenting work, such as house cleaning and daycare services. The GPI estimates the market value of unpaid household labour and parenting. |
| 3 | Adding in the value of higher education | This aspect of the GPI acknowledges the external benefit society receives from well-educated citizens. |
| 4 | Adding in the value of volunteer work | GDP excludes the value of volunteer work, despite clear societal benefits. The value of volunteer work is estimated using a market-wage rate. |
| 5 | Add in the service value of consumer durables | This category attempts to capture the benefits consumers receive from long-life assets providing services, such as cars, furniture and white goods. |
| 6 | Adding in the service value from highways and streets | The GPI excludes most government expenditure as it is of the defensive type (e.g. spending on the military) and not deemed contributory to welfare, however the use of infrastructure such as streets and highways is deemed to be beneficial. |
| 7 | Subtracting the cost of crime | GDP would count the costs of crime as an addition; however crime detracts from social welfare. Therefore the costs of imprisoning criminals and private defensive expenditure such as burglar alarms are deducted. |
| 8 | Subtracting the loss of leisure time | GDP increases when labour hours increase, but fails to distinguish for the loss of leisure time. |
| 9 | Subtracting the cost of underemployment | Underemployment includes members of society who have stopped seeking employment, are working part-time but would prefer full-time, and those will but unable to work due to some form of economic incapacity, such as an inability to afford day care services. |
| 10 | Subtracting the cost of consumer durables | As the GPI includes a monetary value for the stream of services from consumer durables, a deduction must also be factored in for consumer spending on |

| | | |
|---|---|---|
| | | such items. This avoids double counting. |
| 11 | Subtracting the cost of commuting and auto accidents | GDP incorporates the costs of commuting to work as a positive contribution to economic welfare. The GPI, in contrast, regards the time and costs incurred as deductions, as well as injuries and deaths from vehicular accidents. |
| 12 | Subtracting the cost of household environmental defensive measures | Where members of society incur costs for buying air filtration and water purification devices, these are undertaken in response to existing levels of pollution, which is to the detriment of economic welfare. |
| 13 | Subtracting the costs of pollution (air, water and noise) | The GPI deducts an estimated monetary value for each type of pollution. |
| 14 | Subtracting the value of lost wetlands, farmlands and forests | The GPI deducts an estimated monetary value for losses to natural capital stocks, including reductions in ecosystem services, lost recreation services, and declining non-use values. |
| 15 | Subtracting the costs of depleting non-renewable resources | GDP includes as a positive contribution the market value of non-renewable resource extraction. As the stock of resources is reducing, the GPI counts this value as a deduction, estimating an 'implied cost' for future generations. |
| 16 | Subtracting the damages from carbon dioxide emissions and ozone depletion | The GPI incorporates a deduction for the estimated marginal economic damage resulting from a tonne of carbon dioxide emissions, multiplied by the total tonnes emitted. In the case of annual ozone emissions, these have been almost entirely eradicated in most countries after the Montreal Protocol, but ozone damage continues due to past emissions. |
| 17 | Adjusting for net capital investment and foreign borrowing | Net capital investment (gross investment minus depreciation) is assumed by the GPI to increase social welfare and represents an addition. Net depreciation or foreign borrowing is assumed to decrease social welfare and thus would be incorporated as a deduction. |

The ISEW and GPI are measures that adjust the GDP model to better reflect the benefits and costs of economic activity (Wilson and Tyedmers, 2013). Proponents of the GPI argue that its indicator outcome provides a comprehensive measure of societal economic welfare and better describes the current sustainability impacts of economic activity (Talberth et al., 2007; Wilson and Tyedmers, 2013;). Due to its methodological similarities to the ISEW, the GPI has naturally been subjected to an analogous set of criticisms. The GPI's detractors tend to focus closely on its subjective understanding of economic welfare (Ollivier and Giroud, 2010), questionable valuation methods for quantifying long-term environmental damage (Neumayer, 2004), failure to properly represent a measurement of sustainability, and inbuilt assumption of perfect substitutability between capital classes (Neumayer, 1999; Lawn, 2003).

The GPI's sustainability interpretation has been scrutinised. Neumayer (2004) describes the GPI as a present economic welfare indicator that is entirely unable to measure sustainability. Harris (2007) concurs, highlighting the GPI's reliance on the Fisherian notion of 'psychic income' and the lack of any sustainability considerations within this concept. Ollivier and Giroud (2010) contend that the GPI is to some extent a 'halfway house': a measure of both present economic welfare (based on current utility flows) and a sustainability indicator (based on natural capital stocks producing utility in the future). However, Dietz and Neumayer (2006) stress that a combined measure of present economic welfare and sustainability is theoretically impossible. According to their interpretation, the costs associated with the depletion of non-renewable energy resources and other forms of natural capital incurred in the future make little or no difference to present economic welfare (Dietz and Neumayer, 2006).

Neumayer (1999) articulates another perceived weakness of the GPI is the fact that while it sets out to reflect the strong sustainability paradigm, its calculation actually reinforces weak sustainability principles. Neumayer's argument is based upon the fact that the GPI measures losses to natural and produced capital stocks separately. Thus, losses to natural capital stocks can be compensated by increases to produced capital stocks in equal or greater value; perfect substitutability between these two types of capital is assumed in the GPI calculation (Neumayer, 1999). Kubiszewski et al. (2013) contend that although this understanding of the GPI calculation is correct (in the sense that increases in private consumption benefits can be precisely balanced by increases in environmental costs), Neumayer's understanding of what the GPI is striving to measure is flawed. Although the GPI is designed to be reflective of some strong sustainability ideals and its practical application may reveal weak sustainability considerations, it is ultimately intended to measure sustainable economic welfare, not sustainability. Posner and Costanza (2011) also remind their audience that the GPI remains a much less arbitrary measure of economic welfare than GDP, claiming that "it is better to be approximately right than precisely wrong" (Posner and Costanza, 2011, p. 1973).

In their recent comprehensive evaluation of GPI and ISEW studies, Kubiszewski et al. (2013) have again reiterated and illustrated their point via the analogy of additional welfare benefits from greater timber furniture being exactly equal to the welfare losses from a felled forest. However, unlike a forest, timber furniture is unable to provide many vital ecosystem services necessary to sustain future economic activity, which may well include the production of new timber furniture (Kubiszewski et al., 2013). As the GPI can only represent rather than effectively measure sustainability, Kubiszewski et al. (2013) are concordant with Lawn's (2003; 2013) demand for the ISEW to be considered in the light of other environmental sustainability indicators, such as the Ecological Footprint.

Another criticism of the GPI is its reliance on many technical assumptions, not least related to competing methods for valuing the depletion of natural capital stocks, the deduction of defensive expenditures, and the total cost of long-term environmental damage (Neumayer, 2004; Ollivier and Giroud, 2010). Kubiszewski et al. (2013) defend the GPI's use of cumulative long-term environmental damage costs (e.g. for land degradation) by highlighting strong sustainability arguments. The GPI aims to measure the level of economic welfare generated by economic activity, and economic activity itself is only undertaken to generate a level of welfare greater than which can be provided by natural capital stocks alone (Kubiszewski et al., 2013). On this basis, the GPI must deduct permanent losses to natural capital stocks to reflect the strong sustainability paradigm, something it was originally designed to depict.

Ollivier and Giroud (2010) criticise the GPI on the grounds that the many additions and deductions are arbitrary and subjective, reflecting a pre-conceived idea of how society should be. Almost every deduction in the GPI has been subjected to critical scrutiny, mainly because it is not evident whether these costs have already been integrated into household decision making (Lawn, 2005). For instance, private consumption may already be lower than would be the case if the costs of commuting had not already been considered by consumers. As Talberth et al. (2007) admit, due to subjective assessments of what elements contribute to economic welfare, the GPI cannot be considered to represent a fully objective assessment. For example, Talberth et al. (2007) highlight that the GPI corrects for income inequality, but takes no account of issues such as political freedom or gender equality. However, this criticism appears to reflect a misunderstanding of the original purpose of the GPI: to solely measure the sustainability of current economic welfare. Kubiszewski et al. (2013) assert that the GPI is confined to an approximation of the total economic welfare generated by economic activity, not total human welfare per se, which indeed stems from a myriad of wider sources. In summary, the GPI considers whether the marginal benefits of economic activity (and perhaps growth) exceed the marginal costs.

# 3 Accounting for Non-Renewable Energy Resources

## 3.1 Introduction to the GPI's Treatment of Non-Renewable Resources

The GPI is underpinned by the need to maintain the asset base from which the sum of economic welfare is generated. The depletion of non-renewable resources, such as fossil fuels, results in a reduction in income-generating sources of natural capital. The sale of non-renewable resources and monetary flows pertaining to their extraction represent additions to GDP (McDonald et al., 2009). The SNA used to arrive at the GDP statistic makes no adjustment for the depletion of natural assets and associated impacts on economic welfare. National accounts essentially consider natural capital stocks to be infinite resources. During a period when the global population is rising and societies have tended to accrue material possessions with increasing relish, natural capital, as opposed to produced capital, is rapidly becoming a scarce resource (McDonald et al., 2009). Lawn (2008) contends that any society which depletes natural capital by extracting non-renewable resources and then fails to reinvest sufficient proceeds to establish renewable resource substitutes, cannot be expected to sustain the same level of consumption into the future. This understanding harks back to Solow's observation concerning the optimal use of income from non-renewable resources (Solow, 1974), and is implicit within the GPI, which counts the market value of non-renewable resource utilisation as a deduction (Harris and Roach, 2013).

In estimating the monetary value of non-renewable resources, the approach used depends on whether a 'strong' or 'weak' sustainability stance is maintained. According to McDonald et al. (2009), advocates of the strong sustainability paradigm underpinning the GPI seek to invest the proceeds from non-renewable resource use into the development of renewable resource substitutes. In so doing, the stock of diminishing non-renewable resources are gradually replaced. A weak sustainability conviction assumes substitutability between natural and produced forms of capital. On that basis, the sustainability of a certain level of economic welfare and national income is dependent upon the total net investment rate of all forms of capital (minus depreciation) being positive.

This thesis will now explore methods of accounting for the costs of non-renewable resource utilisation. It is argued that a strong sustainability stance requires the full current cost of replacing utilised non-renewable resources with renewable energy alternatives to be deducted from the GPI. It is not sufficient from a strong sustainability stance for merely the resource rents from non-renewable resource depletion (Daly and Cobb, 1989) or user cost to be reinvested into renewable energy alternatives, as this approach permits the future stock of non-renewable resources to continue to decline. These approaches are depictive of the weak sustainability imperative. According to strong sustainability notions, both capital classes must be non-declining separately, and this requires a comprehensive shift away from the use of non-renewable resources. In addition, the natural rates of replenishment of renewable resources must not be exceeded, otherwise natural capital stocks are still denuded, and Chapter 4 considers the importance of this issue in greater depth.

## 3.2 Valuing Non-Renewable Resource Depletion in Monetary Terms

The GPI was first calculated in the United States in the mid-1990s. The methodology used in that project – since also applied to the UK and Swedish GPI studies – measures the replacement cost of the depletion of non-renewable resources (only energy and not minerals) through an estimation of the current market cost of replacing fossil fuels and nuclear energy with renewable energy alternatives (Hamilton and Saddler, 1997). In the United States, their GPI methodology calculates the replacement costs of non-renewable resources using the costs of biomass fuel production. This generic approach is debatable in itself, yet its straight-forwardness is evidently attractive. Talberth et al. (2006) justify the use of biomass fuel on the basis that it comprises the largest share of the renewable energy market in the United States. The GPI in the United States assumes a nominal replacement cost of US $75 per barrel of biomass fuel and makes an arbitrary price adjustment for assumed scarcity: 3% increases per annum for every year after 1988, and 3% decreases for every year prior (Talberth et al., 2006). The total annual non-renewable energy consumption measured in quadrillion BTUs is then converted to its equivalent in terms of barrels of oils, before this figure is multiplied by the adjusted annual replacement cost figure for biomass fuel (Talberth et al., 2006).

It is evident that the academic debate has tended to be concerned with neither whether substitutes can be found for non-renewable resources nor weak and strong sustainability debates. Instead the focus has been mainly concerned with what the correct costs should be during the process of non-renewable resource utilisation (Daly and Cobb, 1989; Hamilton and Saddler, 1997). The replacement cost approach has been criticised by Neumayer (1999), Dietz and Neumayer (2006) and Lawn (2008), all of whom contend that either a resource rent or 'El Serafy' user cost approach is more appropriate. Determining the most appropriate cost deduction is especially important since for most national GPI studies, the costs of depleting non-renewable resource stocks generally represents the largest deduction in the index (Hamilton and Sadler, 1997; Hamilton, 1999).

Such analysis often appears to be ignorant of the main philosophical underpinnings of the GPI – to provide a measure of sustainable current economic welfare that reflects the domain of ecological economics and embeds its strong sustainability paradigm. Although the GPI undoubtedly measures weak sustainability due to its ingrained assumption that growth in consumption benefits can offset environmental and social costs to economic welfare, when calculating specific cost deductions, it strives to reflect the strong sustainability stance on the basis that there are certain environmental functions that cannot be duplicated by produced capital. The sourcing of non-renewable natural capital resources for energy generation to support human economies is just one example of an ultimately finite operation, while the alternative option to use more renewable energy (assuming sustainable yields) is not.

The GPI has been criticised regarding many of its valuation methods for approximating the costs of environmental items, in particular its approach which applies a cumulative cost to land degradation, lost wetlands and long-term environmental damage. As one of the essential aims of the GPI is to reflect current economic welfare generated by economic activity, it is argued that the GPI must subtract for permanent losses to some natural capital services (Kubiszewski et al., 2013). Thus, it is argued, to be consistent with strong sustainability objectives, the GPI should deduct cumulative costs for specific environmental items (Kubiszewski et al., 2013; Lawn, 2005), and therefore the cost deduction also includes what it would have cost past generations to keep the natural capital stock intact. Such an approach appears to have two fundamental weaknesses: (1) the aim of the GPI is to measure sustainable *current* economic welfare; and (2) strong sustainability requires the stocks of produced and natural capital stocks to both be non-declining. The concept of Fisherian 'psychic' income depicts the welfare associated with *current* consumptive activities and their stream of services, including deductions for associated socio-environmental costs and additions for non-market benefits.

It is not possible to provide a measure of *current* economic welfare reflecting past environmental costs, as this infers that current generations should also receive a benefit in the GPI for the consumption benefits that flowed from natural capital depletion occurring at that time. Furthermore, the GPI aims to reflect a sustainable level of economic welfare now with a view forward to the next time period. It is undoubtedly forward thinking in terms of its intergenerational perspective. Strong sustainability ideals can realistically only be measured with regards to the same current and future perspective as adopted overall in the GPI. In other words, assessments of whether capital stocks are non-declining only have meaning in terms of current sustainable economic welfare when evaluated in the same time period. Otherwise, societal compliance and the generation of economic welfare in accordance with strong sustainability objectives next year will (and as we observe *is*) be penalised forever into the future for the actions of past generations. This thesis therefore contends that to be consistent with notions of measuring current sustainable economic welfare and reflections of strong sustainability ideals, the costs of non-renewable resource extraction should be (1) measured in the year of utilisation only; and (2) equivalent to the full replacement market cost of the most suitable renewable energy alternative. This argument is further enhanced when retaining a perspective of what the GPI is trying to measure – current sustainable economic welfare, not environmental sustainability. Measuring the latter concept does indeed demand the incorporation of assessments of long-term and cumulative environmental, and to do so the GPI should always be supplemented with other measures of biophysical stress, such as the Ecological Footprint or Environmental Sustainability Index.

Cobb and Cobb (1994) were the first authors to propose the use of the replacement cost approach when calculating the value of annual non-renewable resource extraction. In their study, each barrel of oil equivalent was valued in terms of the replacement cost of renewable energy.  The price was assumed to increase by 3% per annum between 1950 and 1990, with the value anchored at an assumed cost of US $75 in 1988, considerably lower than the calculated benchmark figure of US $99.10 that was later applied to the GPI in the United States (Talberth et al., 2006). Their justification for constantly increasing replacement costs of renewable energy appears to be flawed. Cobb and Cobb (1994, p.267) justify their approach by highlighting an average 6% per annum increase in the costs per foot of oil drilling since the 1970s, supporting their argument with the assertion that "when the limits of a resource are being reached, the cost of extracting the next unit is more costly than the previous unit". However, although a plausible argument when considering the nature of non-renewable resource extraction, which has scarcity value, they also apply this line of thinking to renewable energy resources, stating that "this principle presumably applies also to renewable fuels, though not as dramatically as to oil and gas" (Cobb and Cobb, 1994, p.267). Using this reasoning they justify the 3% rather than 6% cost escalation factor. Such thinking is erroneous as the costs of renewable energy alternatives tend to remain high because the technologies are in their relative infancy and have not yet gleaned economies of scale. Neumayer (2000) asserts that it is perhaps more appropriate for the replacement costs of non-renewable resource extraction to fall over time.  In the near twenty years since Cobb and Cobb (1994) authored their study, costs for renewable energy have tended to follow a downward path, particularly in the onshore wind and solar photovoltaic markets (Darling et al., 2011).

Neumayer (2000) also takes the replacement cost approach to task for using a total valuation. He believes that only a fraction of the total cost should be used, as non-renewable energy reserves remain for future generations to utilise in the future. Thus, according to Neumayer's understanding, the only justification for applying the replacement cost method would be in a scenario whereby all recoverable non-renewable energy reserves had recently been depleted. However, Lawn and Clarke (2008) contend that Neumayer's critique is ignorant of the Hicksian element embedded within the GPI methodology. The GPI strives to reveal the sustainable nature of economic activity and economic welfare generation. By deducting only a proportion of the total cost of non-renewable resource exploitation, Neumayer's approach fails to recognise sustainability considerations, all the more so in the light of likely price rises for fossil fuels in the future due to increased scarcity (Lawn and Clarke, 2008).

An alternative to the replacement cost method is El Serafy's 'user cost' approach for calculating resource rents, an approach that is advocated by Neumayer. El Serafy (1989) contended that only a proportion of the total profits from depleting non-renewable resources should be set aside for reinvestment into alternatives to maintain a constant (Hicksian) income stream and be deducted from the GPI (or its predecessor, the ISEW). Thus, it is a proportion of profits (or net proceeds) that is deducted from the GPI, not the entire replacement costs (Lawn and Clarke, 2008). El Serafy's user cost theory then assumes that the remaining proportion of net proceeds can be regarded as genuine income, suitable for supporting consumption and providing a stream of services in accordance with the Fisherian notion of income. According to Lawn and Clarke (2008), this remaining portion of net proceeds cannot, on its own, undermine the capacity of nations to sustain consumption over time.

The El Serafy (1989) user cost formula is as follows:

$$\mathbf{X/R = 1 - 1 / (1 + r)^{n+1}}$$

**where X is the true resource rent after investment in replacement assets; R, the total net proceeds (gross proceeds minus extraction costs); X/R is the reserves to extraction ratio; r, the discount rate (or regeneration rate of the resource in the case of a strong sustainability approach); n, the number of time periods over which the resource is to be liquidated*

According to El Serafy's formula, Item X will always include a deduction from R for the amount of total net receipts that need to be set aside to establish a replacement asset and ensure a perpetual income stream. Item X therefore reflects both replacement cost and resource rent considerations. It is the former since the fraction of the proceeds from non-renewable resource extraction that do not constitute a user cost are the genuine costs of resource asset replacement (R – X). It is also the latter as the portion of proceeds that does not equate to a user cost is a resource rent (X).

It is also evident from El Serafy's formula that the only components influencing the fraction X/R will be r and n: the discount rate and liquidity periods respectively. The greater the value of either or both of these two items, the higher the proportion countable as income and lower the amount needed to reinvest into replacement assets. For example, if we assume a fixed value for n of 25, we can compare outcomes with discount rates of 4% and 7% respectively:

**Discount rate r of 4%**

$X/R = 1 - 1 / (1 + 0.04)^{25 + 1}$

$X/R = 0.64$ (2dp)

**Discount rate r of 7%**

$X/R = 1 - 1 / (1 + 0.07)^{25 + 1}$

$X/R = 0.83$ (2dp)

The same effect can be demonstrated via the adoption of a fixed value for r of 5% and comparing liquidation periods 'n' of 20 and 40 years respectively:

**Liquidation rate n of 20 years**

$X/R = 1 - 1 / (1 + 0.05)^{20 + 1}$

$X/R = 0.64$ (2dp)

**Liquidation rate n of 40 years**

$X/R = 1 - 1 / (1 + 0.05)^{40 + 1}$

$X/R = 0.87$ (2dp)

From these two simple comparisons, it can be observed that a company with a discount rate of 4%, seeking to liquidate a non-renewable resource over a 25 year period, can allocate 64% of its net proceeds (R) as income, while the remainder should be reinvested into replacement resources. However, a company with a higher discount rate of 7% and also seeking to liquidate the same resource over a 25 year period should consider 83% of its net proceeds (R) as representing income, and 17% should be reinvested into replacement assets to ensure a perpetual stream of income. Additionally, when comparing a fixed discount rate of 5% with liquidation periods of 20 and 40 years respectively, 23% more of R can be considered to be income over the longer period.

Although mathematically influential, it is important to note that values for r and n are to some extent arbitrary and certainly not fixed over time. Often a discount rate of 3-4% will be chosen as a means of approximating precautionary yields from new investments (El Serafy, 2013). Equally, the extraction schedule is assumed to take place at a constant rate over a fixed time period. Although Lawn (2000) contends that assumptions concerning extraction schedules are reasonably robust, in reality, the owner of the non-renewable resource may change extraction plans, often in response to fluctuations in current and expected market prices and interest rates. In the case of the latter factor and in accordance with the Hotelling Rule, the resource owner may choose to delay extraction if interest rates available for financial investment are lower than rates of resource price appreciation due to increased general scarcity (Fisher, 1977). Furthermore, there is often a degree of uncertainty as to the amount of resources that can be considered 'recoverable' (El Serafy, 2013). Technological improvements can emerge that lead to considerable adjustments to the size and valuation of the recoverable resource, also offsetting anticipated rises in the costs of production.

However, the most fundamental flaw in El Serafy's user cost method is its methodological inappropriateness in the light of the strong sustainability notions behind the GPI. The theory advocates that a fixed proportion of net proceeds should be reinvested into alternative assets to ensure the perpetuity of the income stream. However, El Serafy does not stipulate the nature of the replacement asset. The replacement asset can be sourced from any capital stock, and could therefore be either a renewable energy asset or more non-renewable resources. In contrast to the GPI, which strives to reflect strong sustainability principles, the El Serafy user cost methodology for approximating Hicksian income reinforces the weak sustainability paradigm by assuming substitutability between capital classes. The ecological economics perspective that underpins the GPI asserts that both productive and natural capital classes should be non-declining. As has been discussed, in practice the GPI permits a certain degree of substitutability, yet its methodological shortcomings should not detract from the importance of embracing the philosophy which it aspires to reflect. Thus, according to the strong sustainability paradigm, a non-renewable resource should always be replaced with a renewable asset. In order for El Serafy's user cost method to apply to the GPI, it must first and foremost reflect this consideration.

Embracing the need to replace non-renewable resource extraction with investments in renewable alternatives also has implications for r, the discount rate. Lawn (2000) advises choosing a discount rate equivalent to the real interest rate on the renewable resource. This is equivalent to its natural regenerative rate (Lawn, 2000), and to reflect the strong sustainability approach, it should be the value for r entered into the user cost formula. Lawn (2000) proposes the use of a generic value for r of 5% to reflect the regeneration rate of renewable resources. Although evidently a somewhat arbitrary choice, immediately it can be observed that this is a higher discount rate than the precautionary value of 3-4% that El Serafy notes is commonly applied. Based upon the earlier analysis concerning the impact of higher discount rates, it is now apparent that proportionally less reinvestment is justified into renewable energy alternatives. However, one final and critical assumption must be challenged that overwhelms and overrides this conclusion – El Serafy's assumption of fixed non-renewable resource prices over time. Lawn (2000) considers that the setting aside of X% of the net receipts (R) from production assumes that non-renewable resources prices will remain fixed over time. This assumption was supported by Neumayer (2000) but is improbable, and the evidence of the past few decades suggests that commodity prices are volatile. Lawn (2000) estimates that non-renewable prices will double over the next twenty-five years, and on this basis proportionally twice as many net receipts need to be set aside for reinvestment into renewable assets. Thus, if 20% needed to be retained before and 80%

represented true resource rents, now 40% needs to be set aside and only 60% is a genuine profit. Although not at the time supported by any real trends in non-renewable resource price rises, Lawn (2006) suggests that this should and eventually will happen due to increases in scarcity. In effect, he is actually providing a critique of the capacity of markets to reflect real-time scarcity values.

Daly and Cobb (1989) also consider El Serafy's user cost method to understate the figure that should be used as a deduction in the ISEW/GPI. They articulate that this is because the formula assumes non-renewable resource availability is entirely a function of the relative and absolute scarcity of resources, whereas it is also influenced by the factors of the costs of exploration and extraction. Rather than subtracting a user cost figure based upon the proportion of net proceeds (R), Daly and Cobb (1989) espouse that it is correct to apply the ratio with respect to the total value of all production (R + Y, where Y is inclusive of the costs of exploration and extraction).

It is apparent that both the resource rent and user cost methods are replete with uncertainties and represent a deficient apparatus for application to a measure which seeks to reflect strong sustainability principles. As non-renewable resources are lost via the process of their utilisation, all of the related income should be considered unsustainable from a current economic welfare perspective. Any approach that does not deduct the full replacement cost of utilised non-renewable resources fails to embrace the strong sustainability paradigm. Cobb and Cobb (1994) were the first practitioners to apply the full replacement cost approach. This valuation technique embraces one further concept that differs from the resource rent and user cost methods – the idea that it is the cost of *utilised* rather than *extracted* resources that should be deducted from the GPI. This is logical as it is consumed resources that need to be replaced with renewable alternatives, not extracted, as these may not be consumed in the current time period and might contribute to future sustainable economic welfare. Arguments against the use of the replacement cost method are ignorant of strong sustainability objectives, and tend to reflect the observation that as non-renewable resources are not yet fully exploited, we need not take a full deduction now for their current utilisation: economic welfare can be sustained, at least in part, next year via their utilisation.

Where this thesis departs from Cobb and Cobb's (1994) replacement cost approach is that it does not support an arbitrary 3% increase in the price of renewable energy alternatives to reflect assumed scarcity value. It is expected that resource prices rise as markets appropriate scarcity value. This is not the case with renewable energy, whenever it is harnessed with sustainable yields in mind. As Lawn (2006) notes, over the long-run we are most probably going to have to rely on solar photovoltaic power to replace much of the non-renewable energy generated. Lawn (2006) also observes that solar photovoltaic power was marginally much more expensive in its early stages of development. Now, as the technology has diffused and evolved, the levelised cost of production has fallen and is approaching grid parity (Branker et al., 2011). Moreover, there are generally few scarcity considerations with solar energy as its global influx exceeds the world demand for energy, albeit in more northerly and southerly latitudes access may be constrained during certain parts of the year. Applying an arbitrary scarcity value to the value of alternative renewable energy fuels is an unwise approach. Instead, it is more appropriate to use the current market price of the renewable energy alternative, excluding subsidies. Choosing the correct alternative renewable energy fuel also seems equally arbitrary, and the generic approach applied in the United States demands further review.

We can therefore conclude this section by stating that the correct means of valuing the depletion of non-renewable resources, aggregated across society, is:

$$\text{US \$ } \sum C_{NR} = MP_{RER} * \sum B_{OE}$$

**where $\sum C_{NR}$ is the total cost of annual non-renewable resource depletion; $MP_{RER}$ is the current market price of the renewable energy alternative, and $\sum B_{OE}$ is the total number of barrels of oil equivalent consumed per year*

## 3.3 Reviewing the Valuation of the Cost of Renewable Energy Alternatives

The choice of method for calculating non-renewable resource depletion costs is especially important due to their numerical importance to the final GPI outcome –

Hamilton (1999) asserts that this deduction typically represents an amount equivalent to one third of national consumer spending. For the United States', Swedish and UK GPI's, the authors estimate the costs of depleting non-renewable energy resources, included energy resources (fossil fuels and nuclear energy), but not exploited mineral deposits. This was mainly due to the ease of aggregating utilised non-renewable energy resources and the relative importance of energy as an input compared to mineral resources (Hamilton, 1999). Where the GPI has been calculated at a State level in the United States, often a slightly more detailed approach is taken when calculating the cost deduction ascribed to non-renewable resource utilisation. The Energy Information Association provides state-level figures on consumption of coal, natural gas and petroleum. The amount of coal, natural gas and petroleum is broken down into two categories: electric sector and amount used outside of the electric sector. This allows GPI assessors to pinpoint how much fuel can be replaced by solar and wind energy (for the electric sector) and how much can be replaced by biofuels (non-electric sector). Electricity that is consumed and can be replaced by solar and wind power is multiplied by 8.75 cents per kilowatt hour in accordance with Costanza et al., (2004); Venetoulis and Cobb (2004); Bagstad and Ceroni (2007); and Makhijani (2007).

Measuring the costs of depleting non-renewable energy resources at the national level has generally involved the use of an estimate for replacing all utilised fossil fuels and nuclear energy with renewable alternatives, particularly biofuels. The correct price according to Cobb et al. (1995) is an arbitrary US $ 75 per barrel of oil equivalent in 1988, a figure increasing by 3% per annum thereafter, and decreasing by 3% per annum for years prior to then. The debate concerning whether to apply a full or partial cost deduction for utilised fossil fuels and nuclear energy has been thoroughly explored in Section 3.2, however, to reiterate, this thesis contends that Cobb et al.'s full-cost approach is the correct methodology, as this maintains strong sustainability leanings. However, the validity of the US $75 ballpark figure (plus or minus the 3% inflator/deflator) is questionable.

Hamilton (1999) describes how the Australian GPI methodology has applied a lower than US $75 barrel of oil equivalent deduction. Hamilton's justification for this approach is threefold: (1) many renewable energy substitutes already exist for finite fossil fuels and their costs are falling; (2) there are many options available to extend the life of fossil fuel resources by increasing the efficiency with which they are used; and (3) technological improvements may occur in the future which increase recoverable amounts of fossil fuels. Justifications (2) and (3) are valid points on their own, but not when applied to the GPI methodology and a strong sustainability stance taken to cost deduction components. Whenever fossil fuel reserves (known and currently unknown) are utilised, a degree of substitutability occurs that runs contrary to the strong sustainability motif. However, Hamilton's first point of contention is a valid consideration, and is in itself outside of any strong or weak sustainability debate. Grubb et al. (1991) were perhaps the first set of authors to pinpoint reductions in the unit cost of renewable energy over time; more recent analysis by Popp et al. (2011) further deepens Hamilton's impression that on a global scale the costs of renewable energy production have continued to fall, particularly across the solar photovoltaic, wind energy and biofuel markets.

The Australian GPI used a value of US $50-60 for their barrel of oil equivalent deduction (Hamilton, 1999). Their view could be seen as a moderate perspective, one neither reflecting the replacement cost of US $75 (1988 prices) for all fossil and nuclear fuels combusted, nor the opposite and optimistic extreme whereby a replacement cost of zero is ascribed. However, the so-called 'crude delphi' method used in the Australian GPI retains a considerable degree of arbitrariness – in practice it arrives at the US $50-60 figure by taking a replacement value of $75 per barrel of oil equivalent in 1995 prices for the consumption of oil and natural gas, but a value for coal that is much lower (around $25) due to this fuel's purported lack of scarcity relative to other fossil fuels (Hamilton, 1999). The result is that the Australian GPI takes a deduction for non-renewable resource extraction equivalent to 16% of annual consumer spending, a proportion that is considerably lower than the average of 27-33% that is typical for most nations using a full replacement cost methodology (Hamilton, 1999). This thesis again reiterates that the Australian GPI's approach is ill-equipped to reflect its philosophical foundations, which are underpinned by strong sustainability leanings. The approach to determining the correct full replacement cost should not be distracted by debates concerning the relative scarcity of fossil fuels. The only relevant question for consideration is whether or not the utilisation of non-renewable fossil fuels or nuclear energy is occurring, and what are the most appropriate costs of renewable (and sustainable) alternatives? Strong sustainability in this sense is an absolute premise, and the GPI should count as a cost deduction the depletion of all fossil and nuclear fuels, irrespective of their future availability in 10, 20 or 100 years. This is true even when the costs of the most suitable alternative renewable fuel are exceedingly high.

Other GPI studies are sometimes even more arbitrary and methodologically unsound in their treatment of non-renewable resource depletion. In cases where the El Serafy methodology is applied, the cost deduction outcomes tend to be even lower. For instance, over the period 1990-2006, the Auckland City GPI applied a non-renewable resource cost deduction for the extraction of rock, sand and gravel for building and transport related projects (McDonald et al., 2009). The Auckland GPI takes a very weak sustainability stance and recognises that the depletion of local mineral reserves necessitates the eventual use of resources from further afield, but seems entirely ignorant of the need to also include deductions for non-renewable energy consumption. Despite a relative dearth of available renewable energy substitutes in the Auckland vicinity, this approach fundamentally undervalues the cost deduction that should be applied for non-renewable resource utilisation. Furthermore, the Auckland GPI assumes an arbitrary profit margin for the aggregate extraction industry of 20%, putting aside just 5% of this amount to be invested to cover the future extra transport costs associated with the need to import as compensation for depleted local mineral stocks (McDonald et al., 2009). As a consequence, the cost deduction per year averages just US $ 836,000 at 2006 prices (McDonald, et al., 2009). By 2006, when personal consumption in Auckland was US $S 27,350,000 at 2006 prices, the deduction for non-renewable resource utilisation equated to just 3% of this amount.

At the very least, the lack of an internationally standardised set of criteria for evaluating the costs of non-renewable resource utilisation leads to some wildly different outcomes. Different methodological stances, some more reflective of the weak sustainability approach than others, all convey a certain degree of arbitrariness when choosing the correct value for the cost of renewable energy alternatives. At the same time, it is important for the GPI calculation methodology to remain a relatively straight-forward measure of sustainable economic welfare, thus retaining its ease of understanding for policymakers.

This analysis needs to consider a little further what the appropriate costs for renewable fuel substitutes might be. By applying the 3% inflator to Cobb and Cobb's 1988 valuation of US $75 per barrel of oil equivalent, in 2014 the correct value per barrel of oil equivalent is US $162 (1988 prices). This number is clearly nonsensical when the latest trends in the alternative fuel market are examined. Analysis conducted by Lux Research in 2013 reviewed the cost of 21 biomass-to-liquid and gas-to-liquid fuels. Their findings included the following:

- Methanol-to-gasoline is the cheapest alternative fuel with a cost of either $82 per barrel of oil equivalent (from natural gas) or $75 per barrel of oil equivalent (from waste).
- Out of the range of potential gas-to-liquid approaches, ethanol synthesis has the lowest cost of $80 per barrel of oil equivalent, while Fischer-Tropsch costs $86 per barrel of oil equivalent, however ethanol has less product value due to blending limits and lower energy density.
- Waste biomass could potentially produce 50 billion gallons of ethanol per year in the United States alone. However, due to the challenging processing requirements, an extra $3.60 per barrel of oil equivalent needs to be added to the typical current costs of producing a single barrel of ethanol.

(Choi, 2013)

It is evident that current market costs for ethanol production are approximately half the typical per barrel of oil equivalent deduction applied to the GPI using Cobb and Cobb's traditional approach. Market costs for ethanol are prone to considerable fluctuations, mainly due to variations in annual corn harvests and the subsequent price of this feedstock. However, Khosla (2011) contends that the likely medium term (5 year) cost for ethanol production will be in the region of US $60 to $70, excluding all subsidies. In addition, if the market price for fossil fuels eventually goes up in line with increased scarcity – say to between $150 and $200 per barrel of oil – then higher cost biofuels will be viable too.

This chapter has thoroughly responded to this thesis' second research question concerning how the GPI methodology should best account for costs pertaining to non-renewable resource depletion. Based upon this review, a set of key realisations that are relevant to any GPI study, either regional or national, are:

- The GPI should reflect a strong sustainability stance and take a deduction equivalent to the full replacement cost of utilised fossil fuels and nuclear resources in a given year.
- The GPI should calculate the barrel of oil equivalent costs of renewable energy utilisation for electricity generation and heat generation separately, as the use of a US $75 (1988 prices) barrel of oil equivalent figure for both is likely to be an inaccurate approach. An assumption that the costs of renewable energy fuels are going to rise is flawed, as scarcity considerations should only be relevant to fossil fuels and recent trends suggest that the prices of renewable alternatives are falling, not rising.
- For each nation or region subject to a GPI study, an evaluation of the most feasible renewable energy alternatives (for electricity and heat generation) should be conducted, to include a measure of the current price in barrel of oil equivalent terms. This analysis should be repeated at fairly frequent intervals to ensure that the most appropriate renewable energy fuels are used as the alternatives, and accurate cost deductions for the assessed location should be applied. In reality, a range of different renewable energy fuels could be used as substitutes for fossil fuel consumption, but this approach is the most straight-forward and least influenced by guesswork as to market trends.

# 4 Accounting for the Utilisation of Renewable Energy Resources

## 4.1 Understanding Energy Sustainability and Renewable Energy

The term 'energy sustainability' is linked to the broader concept of sustainable development, with energy resources driving the majority of the world's economic activity (Rosen, 2009). In addition, energy resources – be they non-renewable or renewable – are sourced from the global environment, and wastes from energy processes are commonly released back to the environment for assimilation. Finally, the services stemming from energy use facilitate high living standards and an array of social and cultural amenities (Rosen, 2009). In much the same way that sustainable development represents a much wider concept than economic activity, energy sustainability is not merely concerned with the implementation of renewable energy sources. Rather, it is a more comprehensive consideration of the sustainable use of energy across the whole energy system. As Rosen (2009, p.56) voices, this system includes "processes and technologies for the harvesting of energy resources, their conversion to useful energy forms, energy transport and storage, and the utilisation of energy to provide energy services such as operating communication systems, lighting buildings and warming people in winter." Energy sustainability is thus concerned with the systems that use sustainable energy resources, and the processes that store, transport and utilise those resources in a sustainable manner.

Four central themes and energy sustainability goals emerge from Rosen's conceptualisation (Davíðsdóttir et al., 2007):

1. Increase the technical and economic efficiency of energy use and production;
2. Improve energy security by diversifying the portfolio of energy supply, reduce reliance on imported energy, and securing the long-term availability of energy;
3. Reduce the environmental impact of energy use and production via the use of clean technologies and fuels to ensure that solid and gaseous waste generation and disposal do not exceed the Earth's assimilative capacity;
4. Expand and ensure reliable access to affordable and high quality energy services.

Out of these objectives, the GPI is mainly concerned with the third point, counting as cost deductions most of the negative environmental impacts stemming from energy resource exploitation and encouraging the greater use of renewable energy. In addition, the stream of services that flow from consumption are reliant on reliable energy services, otherwise both consumption and the stream of services itself will be lower, and therefore the fourth theme is also embedded as a principle within the GPI. In terms of the second theme, the GPI is only partially concerned with long-term availability of energy issue. At first glance, this methodological deficiency may not be immediately obvious – after all, the GPI generally takes as a cost deduction the renewable fuel alternative in barrels of oil equivalent for utilised fossil fuel and nuclear stocks. However, the GPI automatically takes a zero cost deduction for its fifteenth component (see Table 2.1) when alternative, so-called 'renewable' fuels are utilised. The assumption made by the GPI is that all alternatives to the utilisation of finite fossil fuels and nuclear resources lead to no loss in terms of sustainable economic welfare.

The GPI does not make a distinction between the pure use of renewable energy and how that energy is used. If rates of extraction exceed rates of replenishment, then even technologies widely considered to 'renewable' are in fact non-renewable, at least in part. Generally it is considered that resource scarcity, an increasing demand for energy and the burgeoning emissions from fossil fuels are the greatest arguments in favour of a transition to greater renewable energy use on a global scale. The essential geological premise underlying the GPI is that fossil fuel reserves are limited, and therefore current and emerging patterns of energy use are unsustainable in terms of their ability to support economic activity. However, the sustainability of renewable energy yields (continuous production at the same rate for a very long time) is of critical importance. As this chapter sets out, renewable energy can diminish economic welfare when used unsustainably – this is again the strong sustainability argument mooted throughout this thesis. In order to begin to refine this assertion a little further, it is important to distinguish between what is meant by 'renewable' and 'non-renewable' energy, and Table 4.1 provides a simple comparison of definitions. Based upon an understanding of what constitutes renewable or non-renewable energy forms, it is possible to then consider important resource utilisation aspects that are currently not incorporated within the GPI.

**Table 4.1: Renewable and Non-Renewable Energy Classification**

| Energy Type | Definition |
|---|---|
| Renewable | Energy occurring from the natural and persistent flows in the environment (Twidell and Weir, 2012). This energy is already passing through the environment as a current or flow, irrespective of there being an installed technology to capture it for wider use. |
| Non-renewable | Energy released from static stores that remain underground unless released by human endeavours (Twidell and Weir, 2012). Examples are nuclear energy and fossil fuel reserves. The energy is initially isolated in terms of its potential, and external human endeavours are needed to extract the supply for use in wider applications. Due to very slow regeneration rates of typically millions of years, this form of energy is commonly accepted to be finite. |

The distinction between the two types of energy is further clarified via the addition of Twidell and Weir's (2012, p.8) list of the five primary sources of useful energy:

1. The Sun;
2. The motion and gravitational potential of the Sun, Moon and Earth;
3. Geothermal energy from cooling, chemical reactions and radioactive decay in the Earth;
4. Human-induced nuclear reactions;
5. Chemical reactions from mineral sources.

The assertion made by Twidell and Weir is that the first three forms of primary energy (excluding geothermal energy from radioactive decay) are responsible for stimulating renewable energy flows. The first form – the Sun – is also the driving force behind the long-term creation of fossil fuels. In terms of this thesis, the main issue of uncertainty and disagreement concerns Twidell and Weir's assumption that all geothermal energy from thermal sources in the Earth's crust can be considered renewable. Geothermal energy is probably the most commonly misunderstood source of useful energy in terms of its renewable characteristics (Rybach, 2003). The Earth's heat reservoir is virtually inexhaustible in terms of human timescales (Stober and Bucher, 2013), and thus the misconception arises that geothermal energy resources are renewable. However, individual sites are much less likely to be sustainable in terms of their resource utilisation. Stober and Bucher (2013) contend that at nearly all geothermal plants, terrestrial heat flow is insufficient to balance utilised heat. It is due to this obvious dichotomy that geothermal resources are chosen for specific focus in this thesis. However, other sustainable utilisation issues related to renewable energy are also important. For example, hydro power is generally considered to be renewable, although the installation of large hydroelectric dams can reduce long-term river flow rates.

Section 4.2 now proceeds by challenging in more detail the embedded assumption that all geothermal energy is renewable, before this thesis applies this critique and proposes methodological expansions to the GPI's cost deduction calculation for non-renewable energy sources.

## 4.2 Geothermal Energy – Is it Renewable or Non-Renewable?

Geothermal energy is widely considered to be renewable (Rybach and Mongillo, 2006; Twidell and Weir, 2012; Hahnlein et al., 2013). In terms of geothermal energy resources, the renewable characteristics relate to the natural state of the energy and the specific characteristics of the resource (Rybach and Mongillo, 2006). Bracketing geothermal energy as 'renewable' would at first appear to be a reasonable approach. Rybach et al. (2000) provide a few statistics concerning the Earth's capacity as a vast heat store, all of which convey the impression of a geothermal resource that is large and essentially ubiquitous:

- The total heat content of the Earth can be estimated to be around $10^{31}$ J and would take $10^{9}$ years to exhaust by today's global heat flow.
- Although lower, the total heat content of the Earth's continental crust (depth to 1 km only) is still 3.9 $10^{8}$ J. Taking into account the world's energy consumption of 474 EJ in 2008, this heat would still be sufficient for around one million years.

- If all of the heat content in the Earth's crust was extracted, it would take approximately $10^3$ years to replenish the store via terrestrial heat flow.

Stober and Bucher (2013), however, contend that high-enthalpy geothermal resources, especially those used for electricity production, are very likely to show strong signs of depletion. Rybach (2003) concords with this point, but remonstrates that reinjection techniques then need to be increasingly introduced. A replenishment deficiency and need for reinjection is exacerbated by economic factors. Often the commercial need for an electricity supply far outweighs any sustainability of use considerations (Rybach et al., 2000). Indeed, as a general observation, Rybach (2003) argues that unsustainable heat extraction can limit the productive lifetime of power plants to only a couple of decades.

In terms of energy use, geothermal energy can be considered neither renewable nor sustainable when it is overexploited (Hahnlein et al., 2013). In such a case, the extracted thermal energy cannot be naturally replenished, and via this unsustainable utilisation, the geothermal reserves become exhausted, and often for an extended period of time. Thus the use-mode determines the renewability of the geothermal energy resource (Hahnlein et al., 2013).

In Section 1.2.3 of this thesis, the frequently cited Bruntland Commission definition of sustainability was described as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (Bruntland, 1987, p. 43). When considering geothermal resources and their utilisation in energy projects, the term sustainability includes the capacity of the system to sustain production rates over a long period of time (Rybach, 2003). Geothermal resources will often be put into production with the primary aim of meeting economic goals (Rybach, 2003). Thus project managers seek a swift payback period on their upfront investment costs, but the effect is that the geothermal reservoir becomes depleted. There are many examples around the world of unsustainable geothermal resource utilisation once production has been instigated. One well-known case is that of the vapour-dominated field of The Geysers in the United States. Figure 4.1 below illustrates a decline in average fluid flow rates of over 150% from 1986 to 1995:

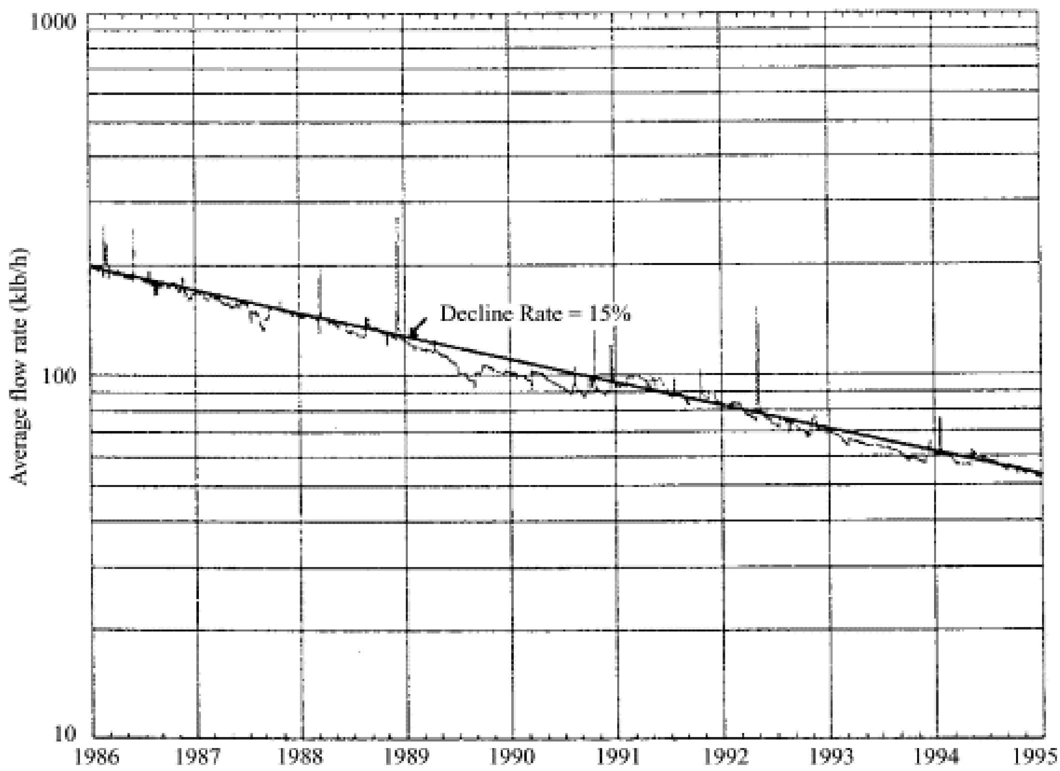


**Fig. 4.1: Average Daily Fluid Flow Rates at The Geysers, 1986 to 1995 (Rybach, 2003)**

Geothermal resources such as those at The Geysers are generally exploited via a withdrawal of fluid and extraction of heat content. Rybach (2003) and Stefansson (2000) consider that there are many cases where such extraction has been achieved in a renewable way for an extended period of time. Indeed, thermal springs around the world have been producing sustained amounts of heat and fluid for centuries, without exhibiting signs of decline. In these cases, a balance has been struck between surface discharge and fluid-heat recharge at depth (Stefansson, 2000). Clearly, where there are scenarios of balanced production and replenishment, these geothermal resources can be considered to be renewable.

It is often the case, however, that balanced production and recharge rates equate to less than satisfactory economic performance for the geothermal resource owner (Stefansson, 2000). Thus, at The Geysers, a geothermal field including 22 power plants provides electricity to an area of around 78 $km^2$, meeting 60% of the power demand for the coastal region between the Golden Gate Bridge and Oregon (Bertani, 2012). Since 1999, and subsequent to the fluid flow rate decline effects illustrated in Figure 4.1, power production began to drop by around 77 MW (Bertani, 2012). This has necessitated the injection of sewage effluent from nearby wastewater treatment plants, thereby topping up the amount of power that can be generated to its previous level. Such an approach is just one example of a commercially-minded response to declining production rates. Other techniques typically involve the reinjection of high enthalpy steam, helping to maintain or restore reservoir pressure, albeit occasionally to the detriment of reservoir temperatures in the short-term (Rybach, 2003). Where reinjection techniques are not utilised and fluid/heat recharge is below production rates, a hydraulic sink in the reservoir accrues (Stefansson, 2000). After resource extraction ends, or production rates are reduced or stop altogether, pressure and temperature gradients typically generate an influx of fluid and heat to gradually re-establish the pre-production scenario (Rybach, 2003). However, full recovery may take hundreds of years, and thus the geothermal resource cannot be considered as the basis for sustainable energy generation and, by dint, sustainable economic welfare. According to Stefansson (2000), power plants for electricity production at The Geysers were originally designed to deliver 2,000 MW, but this output proved unsustainable and fell to 1,500 MW (Stefansson, 2000). Reservoir studies have shown that the sustainable level of production might not be more than 1,000 MW (Stefansson, 2000), approximately half the originally intended output.

Many mathematical simulations have been conducted to try and discover the full recovery timescales for geothermal resources. Rybach et al. (2000) found that recovery exhibits asymptotic behaviour, relatively swift at the beginning before slowing down, with the re-establishment of the initial scenario theoretically attained only after an infinite period of time. However, 'practical replenishment' of 95% or more could be achieved much sooner, and was generally equivalent to around the lifetime of geothermal production systems of approximately 30 to 40 years (Rybach, 2003). However, in the case of high-enthalpy reservoirs – those used for electricity production – practical replenishment could take a few hundred years, depending on local recharge conditions (Rybach et al., 2000). Pritchett (1998) models the nature of recovery rates in high-enthalpy, two-phase geothermal reservoirs used for electricity generation, and concurs that pressure recovery of greater than 95% will take around 250 years, although this time period will be insufficient to result in a commensurate temperature recovery. Pritchett's analysis is summarised in Table 4.2 below:

**Table 4.2: Relative Recovery Rates in Two-Phase, High Enthalpy Geothermal Reservoirs (Source: Pritchett, 1998)**

| Reservoir Properties | Years After Production Shut-In | | |
|---|---|---|---|
| | **50** | **100** | **250** |
| Pressure (%) | 68 | 88 | 98 |
| Temperature (%) | 9 | 21 | 77 |
| Steam Volume (%) | - | 5 | 55 |

On the basis of Pritchett's analysis and depiction of pressure replenishment rates which exceed an average human lifespan, it is ever more important to consider the time period that does constitute sustainable utilisation of the geothermal resource. This is the level that would enable these resources to maintain their 'renewable energy' classification. Much of the analysis concerning the sustainable utilisation of geothermal energy resources has been conducted in Iceland due to widespread utilisation in this country. Axelsson (2010) considers two main issues when the sustainability of geothermal energy resources is being evaluated:

1. The question of whether geothermal resources can be used sustainably at all;
2. The issue of defining an appropriate timescale for consideration.

Point one above concerns the consideration that bracketing geothermal resources as renewable or non-renewable is an oversimplification. Geothermal resources have a twin nature – on the one hand they are an energy current (via heat convection and conduction), and on the other they are a form of stored energy (Axelsson, 2010). Although the energy current is steady (thus entirely renewable), stored energy is always replenished at very slow rates (thus non-renewable), as illustrated in Table 4.2. During the production process, the energy current exceeds replenishment to the energy store. There is thus an opposing nature to the renewable characteristics of the geothermal resource. However, this thesis disputes Axelsson's suggestion in point one that it might not be possible for geothermal energy to be used sustainably – this point essentially highlights a difference between production rates that currently occur in practice due to economic desires and those that are necessary according to theory.

There are, however, difficulties in determining an appropriate timescale for evaluating the sustainable utilisation of geothermal resources, as Axelsson alludes to in his second point of contention. The use of a typical 'economic feasibility' timescale of between 25 and 30 years is too short to accord with the Bruntland definition of sustainable development, which requires an intergenerational perspective. On the other hand, using a geological timescale of hundreds of thousands of years is also inappropriate. Over such a vast period of time, the sustainable potential of the geothermal field would essentially equal the natural flow through the system (Axelsson, 2010). In 2001, an Icelandic working group settled upon a timescale of 100 to 300 years (Axelsson et al., 2001), enough to satisfy an intergenerational perspective, but insufficient to reflect the natural heat flow through the geothermal system. For the purposes of this thesis, maintaining production for the minimum threshold period of 100 years is considered to be a sufficient indicator of sustainable utilisation.

Figure 4.2 depicts the Icelandic working group's definition of sustainable production where heat extraction and replenishment are balanced. The chart uses the term E to refer to the level of production and identifies a fixed level of sustainable production ($E_0$) for a given geothermal well, field or region. Where $E < E_0$ or $E = E_0$, this equates to sustainable production. Figure 4.2 also illustrates the case of $E > E_0$. This is an excessive level of production that will subsequently reduce to below $E_0$ due to the over-extraction of heat in the initial production phase.

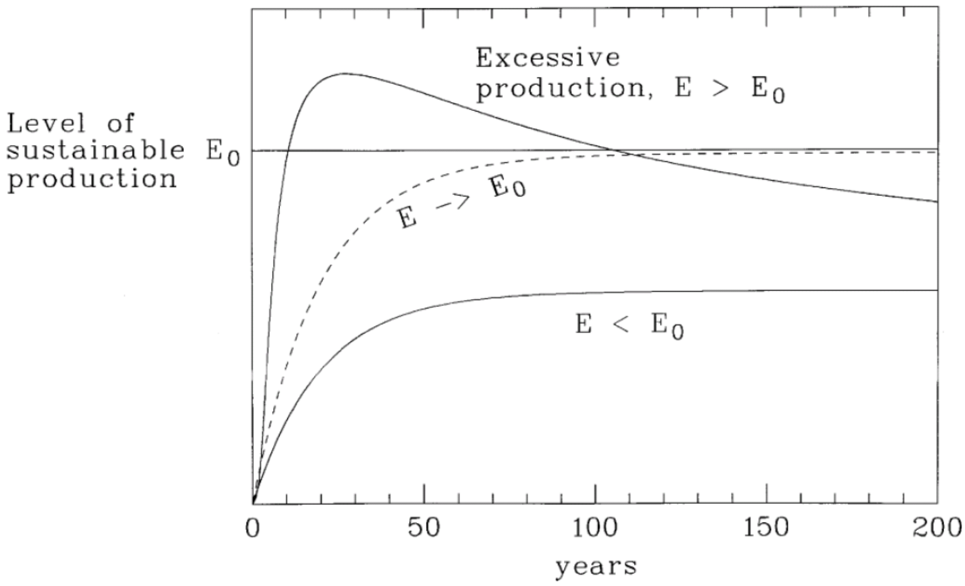


**Fig. 4.2: Schematic Graph Describing the Essence of Sustainable Geothermal Production (Source: Axelsson et al., 2001)**

Although Axelsson et al.'s (2001) model offers a solid theoretical basis for appraising the sustainable utilisation of geothermal resources, in practice determining the level $E_0$ is replete with difficulties. The production level of geothermal resources is generally only understood in terms of approximate parameters prior to commencement. During the first phase of production, much information has to be gathered in order to accurately assimilate the field's capacity (Hahnlein et al., 2013). Thus, in the first few years of production, 'best estimates' based upon typical performance patterns may need to be assumed for the sustainable level of production, $E_0$, with this figure being reconsidered over time in line with gained knowledge. There are now many long-term evaluations of production levels in geothermal resources (albeit the actual figure for $E_0$ remains undetermined), and some of these are considered in further depth in Section 4.3 of this thesis.

Another important issue to note regarding Figure 4.2 is that it does not delineate the nature of the geothermal system – is it a single well, a field or even the entire geothermal resources of a whole country? The figures for $E_0$ and E could, in theory, be arrived at with reference to any of these geographical scales. Axelsson (2010) explains that if a whole country or regional perspective is taken, geothermal systems can be used in a cyclical fashion, where one field is rested and another produces at a rate far in excess of $E_0$, and then vice versa into the future. On this basis, it is possible to conclude that a nation's utilisation of geothermal resources is sustainable, even where there are several fields that are demonstrating a state of overproduction. When considering the GPI, a more robust (but technically challenging) approach would involve an appraisal of the utilisation credentials of each geothermal power plant. This approach is sensible as geothermal power plants owners are often contractually obliged to provide a minimum annual electricity output to industry. Where designated geothermal fields are unable to sustain a required level of electricity output, and therefore substitute, 'top-up' energy resources (presumably geothermal, but not necessarily) need to be harnessed, this is a clear case of overproduction. The replacement natural capital resources would not otherwise have been utilised for this productive purpose. If, on the other hand, the sustainable level of production, $E_0$, was sufficient to fulfil contractual output obligations, then the further harnessing of geothermal energy resources would not necessarily be in conflict with a strong sustainability stance, provided of course that these too were utilised sustainably.

Given the various and differing stances concerning the sustainability utilisation of geothermal resources, it is advantageous to also consider various possible modes of production. These are shown in Figure 4.3 below:

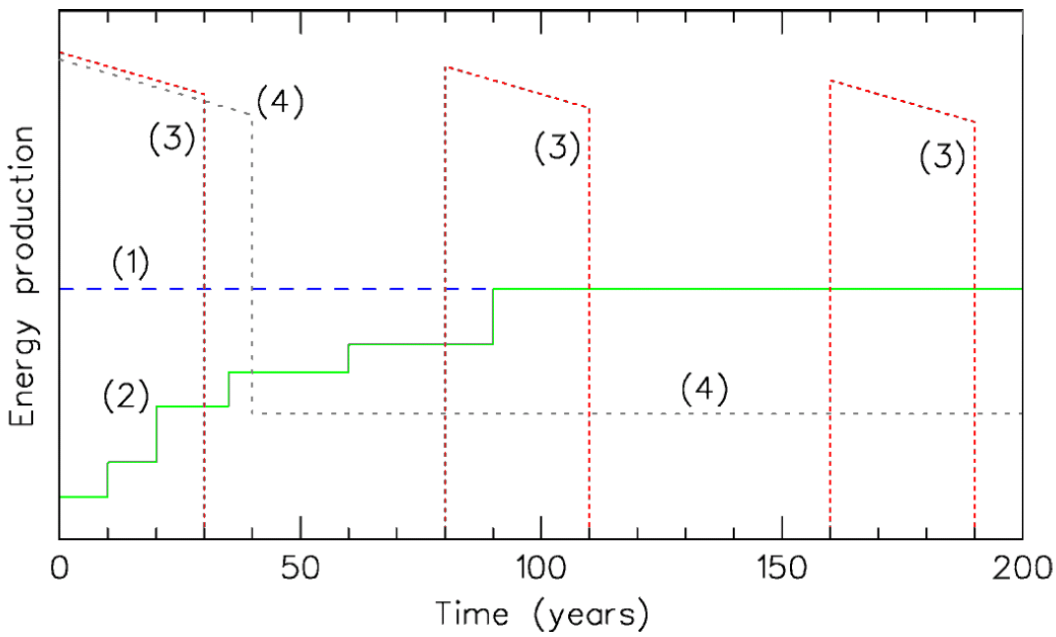


**Fig. 4.3 Production Modes for Geothermal Systems (Source: Axelsson, 2010)**

The chart in Figure 4.3 illustrates four possible production modes at geothermal power plants over a 200 year timespan:

1. Sustainable production throughout – this mode is equivalent to producing at the sustainable production output from the outset and is very unlikely due to knowledge gaps prior to commencement;
2. Stepped production – this mode equates to slow and steady evaluation, gradually increasing the production output and gaining knowledge about the geothermal field, until the point when production eventually (after many years) converges to the sustainable level;
3. Cyclical production – this mode involves intensive harnessing of the geothermal resource and then necessitates the use of other geothermal or alternative energy resources during periods of rest for the primary field;
4. Overproduction and lower production – This mode is a slight variance on mode (3), whereby production is reduced to the lower level $E < E_0$ after an initial period of overproduction, rather than a complete cessation.

Axelsson's (2010) depiction of the cyclical approach to production is evidently an approximation, but it suggests that a thirty year period of production then requires a fifty year period of rest, before another thirty year period of overproduction commences. The level of production in years 80 and 160 is assumed to resume at the same output as year 0. This seems unlikely in the light of the analysis examined earlier by Pritchett (1998) on high-enthalpy, two-phase geothermal reservoirs, which found that after a 50 year shut-in period, pressure and temperature levels recovered by only 68% and 9% respectively. If Pritchett's analysis was applied to Figure 4.3, then it is probable that the maximum attainable production output in years 80 and 160 might still be someway lower than the sustainable production output denoted by the dashed line. As a consequence, additional geothermal or alternative energy sources would need to be harnessed for a much longer period to ensure a fixed level of energy production. As Section 4.4 explores in greater depth, this has relevance to the GPI in terms of a proposed cost deduction ascribed to unsustainable 'renewable' energy utilisation.

## 4.3 Long-Term Geothermal Utilisation Case Studies

Where geothermal fields have been monitored for decades, these sources provide the most credible databank of information concerning sustainable utilisation rates. Modelling studies, based on available data on the structure and production response of geothermal systems, or simulation analysis, are the most adept tools to estimate $E_0$, the sustainable level of production (Mongillo and Axelsson, 2010). These evaluations can also be used to inform resource managers when they are considering the potential benefits of reinjection and the most appropriate utilisation rate in the future. In order for an assessment to be reliable, it is necessary for production data to have been sourced over a period of at least several years, or preferably decades (Axelsson, 2010). Where prospective geothermal fields are yet to be harnessed, their likely sustainable production level can only be calculated in very approximate terms (Sarmiento and Björnsson, 2007). In such cases, response data is not available, and thus an appraisal can only be calculated with reference to the approximate size of the field, temperature conditions and knowledge of comparable systems. Such work is often carried out using the volumetric assessment method, together with Monte Carlo simulation (Sarmiento and Björnsson, 2007).

There are many examples where it has been shown to be possible to produce geothermal energy (with or without reinjection) in a manner such that pressure decline during production is broadly equivalent to the recharge to the system. These case studies predominantly involve low-temperature (less than 150°C) fields, although examples of sustainable utilisation in high-temperature (typically 200°C to 350°C) are known too (Axelsson, 2010).

One of the most well-known and discussed examples of long-term utilisation is the low-temperature Laugarnes geothermal system in Reykjavík, Iceland. The Laugarnes area has been exploited since 1928 through over fifty wells, providing residents of Reykjavík with an abundant hot water supply (Axelsson, 2010). Here semi-equilibrium has been maintained for over four decades. As Figure 4.4 illustrates, despite a fourfold increase in production in the 1960s and corresponding decline in water levels, production levels have been maintained at a broadly constant level from 1970 to 2010.

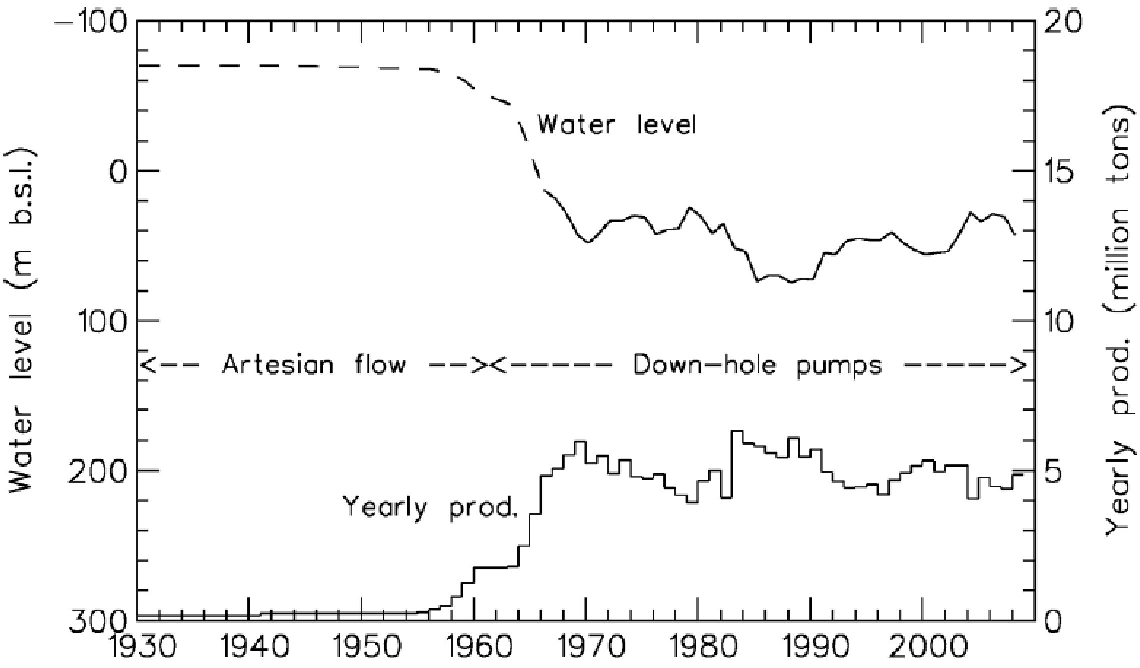


**Fig. 4.4 Geothermal Production and Water Level Characteristics at Laugarnes, 1930 to 2010 (Source: Axelsson, 2010)**

Another example of the long-term analysis of a low-temperature geothermal field concerns the Paris Basin in France, albeit this is a sedimentary resource, not convective tectonic. The Paris Basin hosts a large geothermal resource associated with the Dogger limestone formation, extending over 15,000 $km^2$ (Lopez et al., 2010). Utilisation of the Dogger geothermal reservoir commenced in 1969 and has mainly been harnessed for space heating purposes for approximately 150,000 residences (Ungemach, Antics and Papachristou, 2005). Despite early modelling studies indicating that the field should cool down after around a couple of decades, significant cooling has not occurred even after a period of over four decades. More recent simulation analysis suggests that no cooling or significant pressure depletion will occur to the production wells for at least another 75 years, provided reinjection occurs every 25 years (Ungemach, Antics and Papachristou, 2005). On this basis, it is reasonable to deduce that utilisation is occurring in accordance with the sustainability test of $E < E_0$ and akin to Axelsson's production mode (1) in Figure 4.3.

Other long-term modelling examples of geothermal utilisation often reveal unsustainable production patterns, particularly where a high-temperature field is used to satisfy a high demand for electricity. This Chapter has already considered the example of The Geysers in the United States, where potential production of 2,000 $MW_e$

has ultimately reduced by more than half due to a shortfall in fluid recharge. Other high-temperature geothermal field examples include Nesjavellir in Iceland and the Wairakei system in New Zealand.

Nesjavellir is one of the high-temperature geothermal zones in the Hengill volcanic region in Iceland. Commencing production in 1990, Nesjavellir was first used to supply hot water to the district heating system in Reykjavík, and later cogeneration of electricity and heat occurred. Today, the generating capacity of the power plant is 120 $MW_e$ and 300 $MW_{th}$ (Axelsson, 2010). Using 3D numerical simulation and lumped parameter models, calculations demonstrate that the present rate of utilisation is not sustainable (Axelsson, 2010) i.e. the present production rate cannot be maintained for a period of at least 100 years. Thus far, thermal cooling impacts have been very limited. However, reservoir pressure decline has equated to approximately 14 bars in the period 1990 to 2010, and is set to diminish by another 13 bars in the period 2010 to 2036 (Axelsson, 2010). Pressure recovery is modelled to commence in 2036, but only after an intense 46-year period of production has entirely ended (Axelsson, 2010). Assuming no further production, full pressure recovery is modelled to occur by 2100 (Axelsson, 2010), which seems ambitious when compared with Pritchett's (1998) analysis of rates in high enthalpy geothermal fields.

In Figure 4.5 overleaf Axelsson (2010) provides a model of past and projected production levels at Nesjavellir, which show an almost linear relationship between a fixed production output of circa 580 kg/s between 2004 and 2036, and declining water levels. The open scenario for the water level is deemed to be 'optimistic', and the close is considered 'pessimistic'.

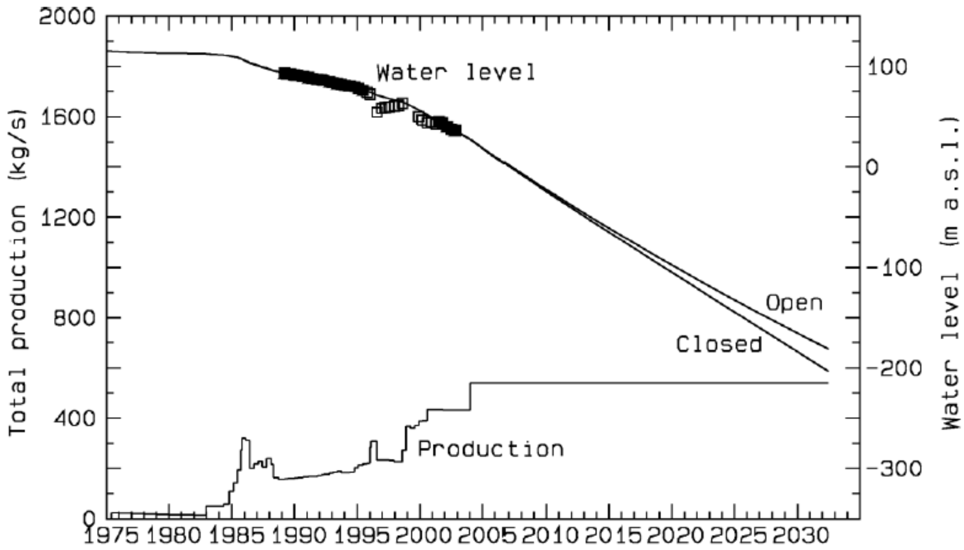


**Fig. 4.5 Production Analysis from Observation Wells at Nesjavellir (Source: Axelsson, 2010)**

The approach to geothermal utilisation at Nesjavellir is indicative of Axelsson's third mode (see Fig. 4.3) –production is cyclical, occurring for an intense period of time, before it is necessary for the geothermal field to rest to allow full pressure and temperature recovery to happen. The precise sustainable level of production, $E_0$, remains undetermined; however the predicted cessation of production in 2036 – a mere 46 years after commencement – is sufficient for the utilisation to be considered unsustainable. In order to maintain the current power plant output of 120 $MW_e$ and 300 $MW_{th}$, substitute energy sources will certainly need to be sourced.

At Wairakei, in New Zealand, utilisation of the geothermal resource commenced in 1958, and recently the average electricity production has been 170 $MW_e$ (Axelsson, 2010). The modelling study at Wairakei had predicted that the geothermal field will be able to sustain production for another 50 years or so (O'Sullivan et al., 2010), thus ensuring that the total production period exceeds 100 years. However, a closer examination of Wairakei's production history reveals entirely unsustainable utilisation of the geothermal resource. During the 1960s, pressure drawdown of up to 25 bars affected production, and lateral inflow of cold water down the original outflow zone of the reservoir became evident in the subsequent two decades (Clotworthy, 2000). These separate problems were overcome through two approaches:

1. Cementing up the wells with shallow downflows of cool water, leading to near constant stability in temperature and pressure levels across the Western Borefield;
2. Replacing production from the Eastern Borefield with production from Te Mihi to the west of Wairakei field.

It was found in the mid-1980s that the Eastern Borefield no longer constituted a high-temperature geothermal resource. The Eastern Borefield wells had been diluted by cool inflows and this strategy, coupled with frequent reinjection, had led to generally reduced field temperatures in the 100°C to 200°C band (Clotworthy, 2000). The replacement geothermal resource, at Te Mihi to the west of Wairakei field, is blessed with temperatures of 255°C to 260°C, which are very close to those originally observed at the undisturbed Eastern Borefield site (Clotworthy, 2000). Thus, since the late 1980s, replacement production has been achieved by tapping Te Mihi's high pressure steam zone, and reservoir modelling suggests that the current level of production (aided by reinjection) will be sufficient for sustained overall production of 170 $MW_e$ until beyond 2050.

Viewed in purely current terms, the Wairakei geothermal field is demonstrating sustainable utilisation as the field is capable of sustaining a consistent production level for at least the minimum threshold period of 100 years. However, current production is sustained through the utilisation of a substitute energy asset. Overproduction across the Eastern Borefield led to the need to utilise Te Mihi as a form of replacement production.

On the basis of this Chapter's theoretical conversation and case study review, it is possibly to clarify a little further and summarise an understanding of what constitutes the sustainable utilisation of a particular geothermal resource:

- A fixed sustainable level of sustainable production, $E_0$, exists for all geothermal systems, albeit knowing this value may require many years of modelling work. Upward or downward revisions to an initial 'best estimate' for the value $E_0$ should be applied as field knowledge increases.

- At an absolute minimum and to accord with the Bruntland definition of sustainable development, production levels should be maintained for a minimum period of 100 years, and preferably up to 300 years.
- Cyclical production (for example, as demonstrated at Nesjavellir) that is unable to sustain a given output level for a period of at least 100 years represents unsustainable utilisation.
- Sustained levels of production for periods of at least 100 years that rely upon the use of a substitute energy resource (for example, at Wairakei) after a certain time are also unsustainable.
- Where initially excessive levels of geothermal production cannot be sustained for more than a few years or decades (for example, The Geysers), this approach also represents unsustainable utilisation.

## 4.4 Theoretical Relevance of Geothermal Energy Utilisation to the GPI

For the purposes of the following analysis, it is assumed that the sustainable production level, $E_0$, is known and fixed from just prior to the commencement of production. In addition, the actual production level is assumed to be fixed or averaged across an annual period. This is a simplification of reality, but is necessary in order to develop some basic principles with regards to whether cost deductions should be applied to the GPI for the unsustainable utilisation of renewable energy resources. Technological advances in drilling technology, monitoring techniques, and the attainment of better utilisation efficiencies may well increase the level $E_0$ over time, and the GPI would be able to capture this as it is a current approximation of sustainable economic welfare. Thus, it is possible that a given level of production that is considered unsustainable in the past and leading to an appropriated cost deduction in the GPI may not deserve the same treatment in the future.

The preceding section considered a range of case studies, and illustrated that many modes of geothermal production are in keeping with a commonly accepted definition of sustainable utilisation. However, equally, many are not, and consequentially this thesis contends that additional costs should be deducted from the GPI. In order to unfold this theory, it is useful to structure the theoretical analysis with reference to Axelsson's (2010) four modes of geothermal production illustrated in Figure 4.3:

### 4.4.1 Mode 1: Sustainable Production Throughout

In this case, the geothermal resource manager ensures that production is maintained at the level $E = E_0$, carefully balancing heat, water and steam extraction with rates of replenishment. This is true for all time periods and production is projected to be maintained for a total period of at least 100 years. On this basis, no cost deduction should be applied to the GPI as the resource can be considered to be utilised in keeping with an accepted definition of renewable energy.

### 4.4.2 Mode 2: Stepped Production

This approach involves a risk-averse and 'stepped' increases in production up to the level $E_0$ after a number of years. In terms of Fisher's 'psychic income' concept, a stepped approach that will converge to the point $E = E_0$ in the future is today merely a failure to maximise potential private consumption opportunities. Once again, no cost deduction should be applied to the GPI as the geothermal resource can be classed as renewable.

### 4.4.3 Mode 3: Cyclical Production

Under a cyclical production mode, a period of unsustainable utilisation will occur for perhaps a few decades, after which a geothermal field is rested and replenishing. This is akin to the anticipated situation at Nesjavellir in the period 1990 to 2036. According to theory, after this year a replacement energy resource would need to be sought until the time when Nesjavellir can be utilised once more. Thus we can be assured that historic production has been $E > E_0$ and will become $E = 0$. After a certain number of years (Axelsson uses a ballpark figure of 60 years), production will resume at the initial level $E > E_0$.

In terms of the GPI, it is important to only consider the situation in terms of current economic welfare and its sustainability. Assuming that the GPI is calculated on an annual basis and the assessment period includes production at the level $E > E_0$, then the difference $E – E_0$ is the unsustainable energy production component. For instance, if the known sustainable level of annual production ($E_0$) from a high-enthalpy geothermal field is 200 $MW_e$, and actual production (E) is 250 $MW_e$, then the unsustainable level of production is 50 $MW_e$. In order for the actual production to be sustainable, a further 50 $MW_e$ of geothermal production would need to be sourced via sustainable utilisation from elsewhere. Some advocates may argue that the diminishment of natural capital resources in the form of geothermal heat and fluid is only a temporary decline, albeit one that may persist for a generation or more. As there are no permanent losses to energy resources, it is therefore possible to argue that even under a strong sustainability stance, the unsustainable utilisation of geothermal resources is an acceptable malaise, and no costs should be deducted from the GPI. However, such a stance is ignorant of the GPI's overall mission: to provide an approximation of sustainable economic welfare in current time terms. The current level of consumption opportunities gleaned from the 250 $MW_e$ level of energy production cannot be sustained for more than a few decades (Axelsson assumes 30 years). As this period is below the minimum commonly accepted threshold for the sustainable utilisation of geothermal resources, it is entirely correct to classify the 50 $MW_e$ of overproduction as unsustainable. This is akin to an argument very briefly outlined by Van Dieren (1995), whereby he asserted that the El Serafy user cost method for non-renewable resource depletion could equally be applied to cases of unsustainable utilisation of renewable resources. According to Van Dieren, a user cost for any level of unsustainable utilisation of renewable resources should lead to reinvestment of sufficient income into substitute resources such that the current level of production can be maintained. This thesis differs from this approach as it recommends the use of a full replacement cost approach for the replacement energy resource.

Having now corroborated the methodological validity of applying a cost deduction to the GPI, the next stage is to consider the correct subtraction to apply. The analysis here requires a similar line of thinking to Chapter 3, which disseminated a detailed examination of the correct costs for substituting non-renewable resources. The same argument applies to renewable energy resources – although a state of overproduction is very unlikely to lead to an entire field drying up, slow rates of heat, fluid and pressure replenishment will ensure that long-term production rates could only be maintained in the future in the band $E < E_0$. The practice of commencing geothermal energy production at the level $E > E_0$ is commonplace and has been justified on the grounds that sustainable geothermal utilisation is a much broader concept than the mere maintenance of a sustainable level of production (Axelsson, 2010). As the introduction to Chapter 4 espoused, the sustainable energy concept is based on four central and often conflicting themes incorporating all aspects of human needs and activity, as well as the importance of mitigating environmental impacts. The competing nature of these objectives has led some advocates to believe that progress towards sustainable development can be achieved via excessive production (i.e. $E > E_0$) if this is outweighed by improved social and economic conditions. However, this thesis defends the strong sustainability stance underpinning the GPI and contends that any form of production in the $E > E_0$ band leads, in current economic welfare terms, to a depletion in natural capital stocks. The GPI recognises the costs associated with the utilisation of non-renewable energy resources, not on the basis that there are no remaining fossil or nuclear fuel sources for future generations to combust, but that ultimately, at some point in the future, the stock of extractable resources will be denuded and renewable energy substitutes need to be sought.

In most cases, unsustainable geothermal production will ultimately be replaced with more geothermal production, as was the case at the Wairakei field. This may not always be the adopted approach. The use of high-enthalpy fields for large-scale electricity production is unwise from a sustainability perspective – The Geysers, Nesjavellir and Wairakei illustrate this. The most suitable alternative energy resource in Iceland might be considered to be hydro power; in others locations in the world even fossil fuel combustion might be the only feasible alternative. It is important to determine the most probable next best alternative, and a simple local feasibility study can be carried out to gather this knowledge. In order to maintain the relative straightforwardness of this analysis and general focus on Icelandic, the costs of an additional 50 $MW_e$ of energy resources is modelled from geothermal (flash) and hydro power sources.

Levelised energy cost (LEC) is one measure that is commonly used to compare the different costs of generating technologies. LEC is a discounted economic assessment of the cost of the energy-generating system including all the costs over its lifetime: upfront investment, operations and maintenance, fuel, and opportunity cost of capital (MacKay, 2008). It can be defined in a single formula as:

$$\mathrm{LEC} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

**Where LEC is average lifetime levelised energy generation cost; $I_t$ is investment expenditures in the year t; $M_t$ is operations and maintenance expenditures in the year t; $F_t$ is fuel expenditures in the year t; $E_t$ is electricity generation in the year t; r is discount rate; and n is the life of the system*

LECs are frequently calculated over 20 to 40 year timespans, and are given in the units of currency per kilowatt-hour (kWh) or per megawatt-hour (MWh) (Wright et al., 2013). Although a very useful measure, it is important to be observant of the many different assumptions used when arriving at LEC estimates. Comparisons of LEC in a local rather than international context are undoubtedly best when considering the GPI cost deduction, albeit data availability constraints may prevent such an approach (MacKay, 2008). For instance, although a global average LEC for geothermal of 65 US $ per MWh is quoted in this thesis, a figure as low as US $ 39 per MWh has been reported in China (World Energy Council, 2013). In this theoretical pontification, the latest LEC estimates from the World Energy Council (2013) shall be used. Table 4.3 below considers the range of LEC estimates based upon global market averages. These LEC figures have already been scaled down with respect to typical load factors for each technology.

**Table 4.3: LEC of Electricity Production (World Energy Council, 2013)**

| Energy Generating Technology | LEC (US $ per MWh) |
|---|---|
| Geothermal (flash) | 65 |
| Hydro power (dams of greater than 10 MW) | 163 |

Returning to the example in this section, it is known that 50 $MW_e$ of production is unsustainable from a given geothermal power plant. On an annual basis, 50 $MW_e$ is equivalent to 438,000 MWh of production, assuming constant power plant deployment. It is now possible to provide generic estimates of the cost values that should be applied to the GPI when considering the ‘next best alternative’ technologies listed in Table 4.3.

The values in Table 4.4 are simply the product of LEC and total MWh of energy production per year, and thus in a simplified world of a single power plant, the GPI cost deduction should be calculated using the following formulae:

**GPI Cost Deduction (US $, 2013 prices) = Annual Energy production (MWh) * LEC of Best Alternative Technology**

Table 4.4 applies this formula to the global LEC averages for geothermal (flash) and hydro power.

**Table 4.4: Estimated GPI Cost Deduction for Different Alternative Energy Options to Unsustainable Production of 50 $MW_e$ from Geothermal Utilisation**

| Energy Generating Technology | Estimated GPI Cost Deduction (US $, 2013 prices) |
| --- | --- |
| Geothermal (flash) | 28,470,000 |
| Hydro power (dams of greater than 10 MW) | 71,394,000 |

Section 4.5 of this thesis considers in greater detail the likely significance of these cost deductions in terms of the overall GPI. Chapter 5 (Discussion) also elaborates a little further on the many assumptions and practical issues associated with calculating the correct cost deduction to apply to the GPI.

It is also important to consider the situation in the third mode whereby production at the geothermal power plant is zero. At a certain time, the plant will be resting and replenishing. In this case, a substitute energy resource has been harnessed, most probably further geothermal resources in a nearby locality. No further cost deduction should be applied to the GPI for the replenishing geothermal power plant now producing at the level E = 0, since the unsustainable rates of utilisation occurred in the past. In current economic welfare terms, the current practice of zero production is sustainable, and the consumption value in the overall GPI calculation will have 'reduced', although it will be increased again via the supply of consumed energy from the substitute resource. Thus the critical issue here is purely whether the substitute energy resource is currently being utilised sustainably. When considering the possible

GPI cost deductions in Table 4.4, the question of whether the overproducing geothermal power plant was a replacement asset was not asked. It is irrelevant in terms of the GPI's measure of current economic welfare. What matters is whether the producing geothermal energy resource itself is utilised sustainably or not. Thus, if the substitute geothermal resource also had a value for $E_0$ of 200 $MW_e$ and was producing at 200 $MW_e$, then no further cost deduction should be applied to the GPI in relation to utilisation rates. It is more likely, however, that the level of output will at least match the 250 $MW_e$ of the now resting and replenishing geothermal power plant. Although the sustainable level of production, $E_0$, will be different for the substitute energy resource, it is likely that it too will demonstrate unsustainable utilisation, albeit the GPI cost may be lower or higher than was estimated for the original geothermal resource.

### 4.4.4 Mode 4: Overproduction and Lower Production

Finally, it is necessary to consider Axelsson's fourth mode of production: an initial phase of overproduction ($E > E_0$) followed by a period of lower production in the band ($E < E_0$). Where the GPI is assessed during a period of unsustainable utilisation, the same methodological approach to cost deductions should be applied as advised in Section 4.4.3. Otherwise, geothermal energy production is leading to a derived scenario of substitution, an approach that is supportive of the weak sustainability paradigm.

An interesting theoretical dilemma concerns the case whereby current field production levels are in the band $E < E_0$ and total field production can still be sustained for a period of at least 100 years. Assuming no replacement energy assets are harnessed to offset the reduction in generation, then in purely the GPI's *current* economic welfare terms, it is the case that the production level is sustainable, and therefore no cost deduction should be applied. This approach may at first appear counter-intuitive, but it is evident that at the current time, no further natural capital resources have been utilised to try and reach the production level $E_0$. The cost deductions applied by the GPI to unsustainable geothermal utilisation have been appropriated to previous assessments. Also, in Fisherian 'psychic income' terms, any period when $E < E_0$, the stream of services flowing from the consumption of energy products is reduced, and thus applying an extra cost to the GPI for past utilisation misdemeanours would equate to double counting. As has been explored, this approach to production is equally the case when Axelsson's second mode of production is applied by geothermal resource owners. A stepped approach that eventually converges to the point $E = E_0$ merely results in a failure to maximise consumption opportunities for citizens.

## 4.5 Applying Unsustainable Energy Utilisation Costs to the GPI

### 4.5.1 Estimated Costs of Non-Renewable Energy Utilisation

As a GPI calculation has not been published for Iceland, it is necessary to create a baseline estimate to assess the potential impact of non-renewable and unsustainable 'renewable' energy resource cost deductions against a full GPI per capita calculation. A useful starting point is a recent seventeen nation study based upon existing GPI and ISEW calculations that established an approximation of the global GPI per capita (Kubiszewski et al., 2013). There are many different methodological approaches encompassed within the studies – for instance, some count cumulative greenhouse gas emission damage, some count only annual flows – but the underlying approaches to the calculation are broadly similar to each other.

The Icelandic GDP per capita in 2013 was US $ 39,996 using PPP (Statistics Iceland, 2014), an amount equivalent to US $33,531 in 2005 prices. Total Icelandic consumption in 2013 was US $7,157,462,592 at PPP and 2005 prices, or US $21,978 in per capita terms (Statistics Iceland, 2014). The ratio of average global GDP per capita (US $ 9,900, 2005 prices) to average global GPI per capita (US $ 3,800, 2005 prices) is 2.61:1 (Kubiszewski et al., 2013). Applying this generic scale factor to the Icelandic GDP per capita it is evident that a reasonable ballpark estimate for the nation's 2013 GPI per capita is US $12,847 at 2005 prices (Kubiszewski et al., 2013). This outcome is by definition inclusive of a cost deduction for the utilisation of non-renewable energy resources.

The combined sum of fossil fuel resources consumed in Iceland in 2013 was 33 PJ (Petajoules), sourced from 29 PJ and 4 PJ of oil and coal respectively, and this is equivalent to 5,629,939 barrels of oil equivalent (Statistics Iceland, 2013). Using the methodology recommended in Chapter 3 of this thesis, an assumed value of US $85 per boe for the best-alternative of biofuel use (2005 prices), and a known population of

325,671 on 1st January 2014 (Statistics Iceland, 2014), the estimated Icelandic GPI per capita of $12,847 (2005 prices) should thus be *inclusive* of the following estimated per capita cost deduction calculated in Table 4.5:

**Table 4.5: Calculation of Estimated Icelandic GPI Costs for Non-Renewable Energy Utilisation, 2013**

| Component | Value |
|---|---|
| Annual fuel consumption (boe) | 5,629,939 |
| Estimated price of biofuel (boe, 2005 prices) | US $85 |
| Estimated Total Costs (Fuel consumption * price) | US $ 478,544,815 (2005 prices) |
| **Estimated Per Capita Cost Deduction** | **US $ 1,469 (2005 prices)** |

Table 4.6 considers the relative importance of the costs for estimated non-renewable energy utilisation against the GPI's starting point of consumption data. A figure of 6.68% seems very low – other GPI studies have uncovered a typical value of 31% (Ericksson et al., 2013) – but this is indicative of Iceland's relatively fossil-fuel free economy.

**Table 4.6: Analysis of Estimated Icelandic GPI Costs for Non-Renewable Resource Utilisation, 2013**

| | Monetary Value in US $ (PPP, 2005 prices) | Percentage of 2013 Consumption Per Capita |
|---|---|---|
| GDP Per Capita | 33,531 | |
| Consumption Per Capita | 21,978 | |
| Non-Renewable Utilisation Per Capita Cost Estimate | (1,469) | 6.68 |
| Inferred other GPI cost deductions | (7,662) | 34.86 |
| **Estimated Per Capita GPI** | **12,847** | **58.45** |

### 4.5.2 Estimated Costs of Unsustainable 'Renewable' Energy Utilisation

This section attempts to apply the cost deduction method advised in this thesis, although it should be recognised that to a considerable extent this analysis is conjecture due to an absence of available data for the sustainable level of production from geothermal fields, $E_0$. The example of unsustainable geothermal utilisation is used once more as this is the most prominent example of a purportedly renewable technology that is frequently harnessed in an unsustainable fashion.

This case study examines the potential impact to the final GPI statistic of unsustainable geothermal utilisation in Iceland. This nation has in recent years experienced rapid growth in its exploitation of high-enthalpy geothermal resources, particularly to facilitate electricity generation to serve heavy industry. Iceland has become comfortably the world's largest producer of electricity on a per capita basis – 54 MWh per capita compared to an EU average of 6 MWh per capita – and over 99% of national electricity production is derived from renewable sources (Orkustofnun, 2013).

Approximately 85% of the total primary energy supply is Iceland is sourced from domestic renewable energy sources (almost entirely from geothermal and hydro power). The remaining share of fossil fuels (15%) predominantly comprises oil consumption in the transport sector (Orkustofnun, 2013). Iceland's geothermal sector delivers:

- 65.0% of total national primary energy production (155 PJ out of 238 PJ)
- 27.3% of total national electricity production (4,701 GWh out of 17,210 GWh)
- 24.8% of installed capacity in power plants (663 MW out of 2,668 MW) (Orkustofnun, 2013)

The total installed electricity generating capacity of geothermal power plants in Iceland is 661 $MW_e$ (Orkustofnun, 2013). Major geothermal power plants in Iceland include Nesjavellir (300 $MW_t$ and 120 $MW_e$), Reykjanes (100 $MW_e$), Hellisheiði (400 $MW_t$ and 303 $MW_e$), Krafla (60 $MW_e$), and Svartsengi (150 $MW_{th}$ and 76.4 $MW_e$) (Orkustofnun, 2013). As Figures 4.6 illustrates, most of the growth in geothermal electricity generation has occurred since the year 2000, especially post 2007 with the commencement of production at Hellisheiði. In 2012, the aluminium industry was responsible for 71% of national electricity consumption (Orkustofnun, 2014).

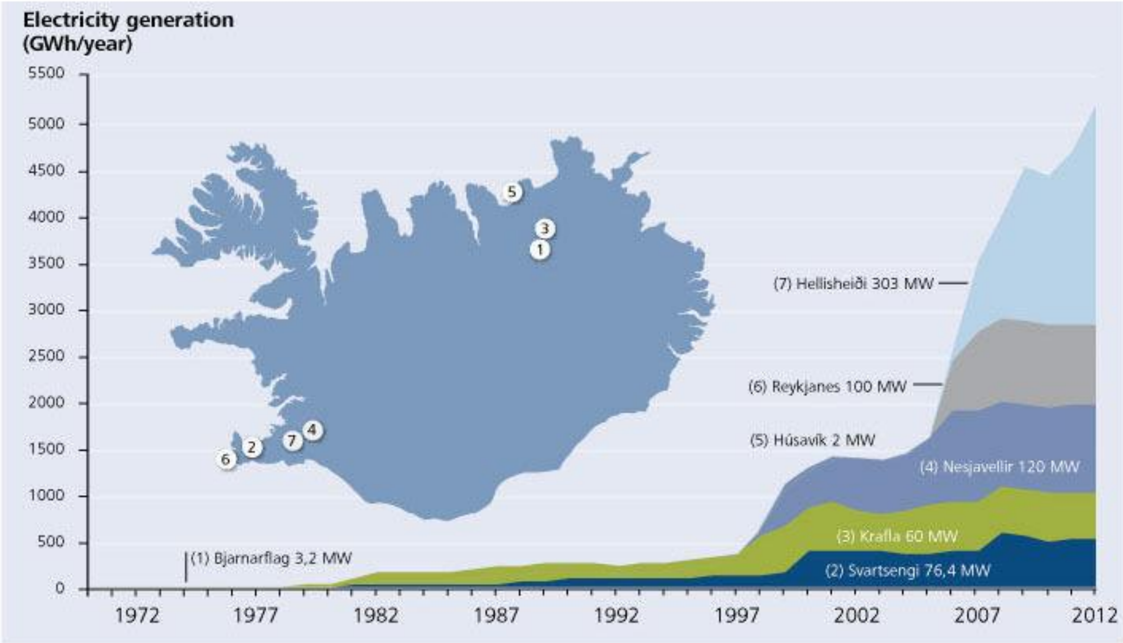


**Fig. 4.6: Electricity Production from Icelandic Geothermal Power Plants, 1970 to 2012 (Source: Orkustofnun, 2014)**

The case study review identified that the renewable credentials of geothermal energy production are particularly likely to be compromised when high-enthalpy fields are used for electricity production – this was apparent at The Geysers, Nesjavellir and Wairakei. This is not to say that geothermal production in binary power plants is necessarily sustainable for a period of 100 years or more. However, this analysis shall remain focused on flash steam power plants which are intensively extracting the geothermal resource to generate electricity. This approach is particularly relevant to the current situation in Iceland. In 2013, it was reported that the Hellisheiði power plant was not able to function at its full capacity of 303 $MW_e$, and could only generate 276 $MW_e$ (Hávarðsson, 2013). Furthermore, scientists asserted that a contractual obligation to sustain fixed annual production of 244 $MW_e$ for Century Aluminium's plant in Grundartangi was likely to lead to an average 6 $MW_e$ reduction in generation per annum (Hávarðsson, 2013). Thus, if this expectancy was borne out, in another 6 years Hellisheiði would be unable to generate sufficient electricity to fulfil its contractual obligations to the aluminium industry, and a substitute energy resource would need to be found. The pattern at Hellisheiði is aligned with Axelsson's (2010) fourth mode of geothermal energy production – overproduction in the initial phase, followed by a much lower level of production thereafter. The academic theory dictates that the depleted steam resource at Hellisheiði will then need to be topped up by a substitute resource. Already plans are underway to connected Hellisheiði's power plant by steam pipes with a nearby high temperature field in Hverahlið (Hávarðsson, 2013).

In the light of serious ongoing concerns in Iceland regarding the unsustainable utilisation of the nation's geothermal resources, this exercise represents an important first step in assimilating the potential order of magnitude of GPI cost deductions for the unsustainable utilisation of 'renewable' resources. The analysis shall again utilise the baseline GPI per capita estimate established in Section 4.5.1.

Knowledge of the level $E_0$ for all electricity producing geothermal power plants in Iceland would be invaluable. This thesis is only able to examine the evidence and contend that the current level of production is excessive, and certainly not in keeping with Axelsson's minimum sustainability threshold of a fixed level of production for a period of 100 years. It is therefore necessary to contemplate the range of possible GPI cost deductions. This thesis now models the impact of 10%, 20%, or 40% of Iceland's total electricity production from geothermal resources as being currently in the unsustainable band, $E - E_0$. Assuming constant production through the year and based upon a national installed capacity of 661 $MW_e$, the total national output of electricity per year would be 5,790,360 MWh.

This speculative analysis assumes that the next best alternative technology to the unsustainable component of geothermal utilisation is either geothermal or hydro power. After factoring out possible resources that are very unlikely or forbidden to be developed for environmental reasons, the potential total generation of electricity in Iceland is commonly purported to be 50 TWh: 30 TWh from hydro power and 20 TWh from geothermal (Valfells, 2008). Current electricity production is approximately 17.2 TWh (12.5 TWH from hydro power; 4.7 TWh from geothermal), leaving 32.8 TWh (17.5 TWh from hydro power; 15.3 TWh from geothermal) of potentially exploitable renewable resources (Orkustofnun, 2013). Although the environmental sustainability credentials of the remaining 32.8 TWh of exploitable potential have been questioned, the availability of spare capacity and lack of viable alternatives embellishes the assumption that these technologies are the most likely replacement energy assets for unsustainably utilised geothermal resources.

Table 4.7 explores the likely costs based upon various degrees of unsustainable utilisation across all of Iceland's electricity generating geothermal resources. The costs of geothermal energy and hydro power are based upon average LEC estimates for Iceland published in the 'Master Plan for Hydro and Geothermal Energy Resources – 1999 to 2010' (Rammaáætlan, 2011). When adjusted to reflect 2005 prices, these figures become US $65 per MWh and $60 per MWh for hydro power and geothermal respectively. These figures have been calculated based on capacity factors of 73% and 94% for hydro power and geothermal respectively. For each of the possible outcomes, per capita cost deductions are provided in brackets underneath the total cost.

**Table 4.7: Projected GPI Cost Deductions for the Unsustainable Utilisation of Electricity Generating Geothermal Resources, 2013 (2005 prices)**

| Assumed Proportion of Electricity Generation Unsustainable ($E > E_0$) | Unsustainable Annual Electricity Generation (MWh) | Cost of Geothermal Replacement (US $, 2005 prices) | Cost of Hydro Power Replacement (US $, 2005 prices) |
|---|---|---|---|
| 10% | 579,036 | 34,742,160<br>(107) | 37,637,340<br>(116) |
| 20% | 1,158,072 | 69,484,320<br>(214) | 75,275,280<br>(231) |
| 40% | 2,316,144 | 316,501,076<br>(428) | 150,549,360<br>(462) |

Depending upon the choice of substitute energy resources and the overall degree of unsustainable geothermal utilisation, a wide range of varying cost deduction outcomes arise. Table 4.8 examines the impact of these possible cost deductions on the per capita GPI, with percentage reductions from the figure of US $12,847 listed below each entry in brackets.

**Table 4.8: Net GPI Per Capita Outcomes After Deduction of Costs for the Unsustainable Utilisation of Geothermal Resources, 2013 (2005 prices)**

| Assumed Proportion of Generation Unsustainable ($E > E_0$) | GPI Net of Replacement Geothermal Costs (US $, 2005 prices) | GPI Net of Replacement Hydro Power Costs (US $, 2005 prices) |
|---|---|---|
| 10% | 12,740<br>(0.83) | 12,731<br>(0.90) |
| 20% | 12,633<br>(1.66) | 12,616<br>(1.80) |
| 40% | 12,419<br>(3.32) | 12,385<br>(3.60) |

The choice of a 10-40% proportion of unsustainable 'renewable energy' generation is entirely arbitrary, but remains an eminently realistic estimate. There remains a risk that the national aggregate level for $E_0$ is either less or more unsustainable than this band; all that can be certain based upon the long-term and emerging evidence from Nesjavellir and Hellisheiði respectively is that there is some degree of unsustainable production that should be reflected in the GPI. However, assuming that the 10-40% band of unsustainability is correct and ignoring the weakness of using global averages for LEC data, it is evident that between a 0.90% and 3.60% cost deduction should be applied to the GPI, depending on the choice of alternative energy technologies. It is of course possible that a mixture of the two technologies could be harnessed to replace the unsustainable component of geothermal production, and then the GPI cost estimates would differ. Furthermore, this thesis has only evaluated the possible GPI cost impacts associated with high-enthalpy geothermal resources capable of generating electricity production. Iceland's low-temperature fields may also demonstrate unsustainable production, particularly in the capital region, and these too should have their sustainability credentials evaluated with respect to the next best alternative energy resource: further production from binary sources.

Finally, it is possible to obtain an estimate for the total GPI cost deduction that should be applied in 2013 for the utilisation of non-renewable and unsustainable 'renewable' energy resources. For the purposes of this analysis, Table 4.9 assumes a mean unsustainable geothermal energy generation of 20%, with a 50:50 replacement asset split between geothermal and hydro power resources, equating to a per capita cost deduction of US $223 (2005 prices).

**Table 4.9: Estimated Icelandic GPI Calculations Including Costs for Non-Renewable and Unsustainable 'Renewable' Energy Utilisation, 2013**

| | Monetary Value in US $ (PPP, 2005 prices) | Percentage of 2013 Consumption Per Capita |
|---|---|---|
| Consumption Per Capita | 21,978 | |
| Non-Renewable Utilisation Per Capita Cost Estimate | (1,469) | 6.68 |
| Inferred Other GPI Per Capita Cost Deductions | (7,662) | 34.86 |
| Unsustainable 'Renewable' Utilisation Per Capita Cost Estimate | (223) | 1.01 |
| **Estimated Per Capita GPI** | **12,624** | **57.44** |

It is estimated that the initial and known starting value for the Icelandic GPI, private consumption, is reduced by a total of 7.69% using the cost deduction methods for non-renewable and unsustainable 'renewable' energy utilisation advised in this thesis. As has been discussed, data absences ensure that the cost estimates incorporate a significant margin of error. However, the strong sustainability and Fisherian lines of thought underpinning the proposed methodology is entirely in keeping with the ethos of the GPI. Chapter 5 (Discussion) further justifies the recommended accounting methodology for the costs of energy utilisation in the GPI and, most importantly perhaps, explores the steps necessary to transform theory to practice.

# 5 Discussion

## 5.1 Accounting for Non-Renewable Energy Resources

An evolving interest in the interaction between the economy and the environment led to the creation of the ISEW and its successor, the GPI. In the GPI methodology, the depletion of non-renewable resources is viewed as a cost borne by future generations that should be subtracted from the capital account of the present generation. Current welfare is adjusted for the reduction in the welfare of future generations caused by the depletion of the resource. Chapter 3 of this thesis provided a detailed discussion of the merits of the replacement cost method over an El Serafy user cost alternative when accounting for non-renewable resource depletion. Chapter 5 begins by considering a little further the possible implications of either approach.

If the user cost method is adopted, depletion of natural capital in the form of whole or part of resource rent is deducted from GDP. The estimated depletion variable is influenced by extraction techniques, market prices and discount rates. In accordance with the Hartwick Rule, it is sufficient for resource owners to invest resource rents arising from the depletion of natural capital stocks in order to maintain sustainable consumption. The key issue is that the investment is permitted to occur in produced capital stocks, and thus the user cost method embeds weak sustainability principles into the GPI.

Many questions arise when attempting to apply to the GPI a cost deduction based upon resource rents. As the resource rent (value 'R' in El Serafy's formula) is essentially market price minus extractions costs, it is important to consider what happens if the market price rises and the costs of extraction remain the same. Does this mean that the resource is more valuable? If the increase in market price is due to higher demand then in terms of the GPI, the user cost deduction method is reflecting how much the current generation values the non-renewable resource, not necessarily the sustainability of current welfare with a perspective fixed on future generations. Moreover, if the market price was to fall and extraction costs remain the same, should the value of the resource also diminish as its scarcity increases? Equally, if extraction costs happen to differ from nation to nation, or indeed over time, the user cost method infers that those countries with higher extraction costs value the non-renewable resource less. These questions have led to the need for an alternative means of calculating GPI cost deductions for non-renewable resource utilisation.

The concept of compensating future generations for the depletion of natural capital stocks is an embedded principle within El Serafy's user cost method. Indeed, it does comply with the Hartwick Rule, which requires capital stocks to be maintained intact. However, the replacement cost method goes a step further by integrating the cost of replacing utilised non-renewable resources with renewable substitutes that provide the same or very similar function.

The primary goal of the replacement cost approach is to provide the GPI with an estimated deduction for the costs of replacing depleted non-renewable assets. It is based on the same premise as the environmental function principle developed by Hueting (1996), and thus it is the environmental function of the depleted resource that needs to be preserved. Thus, the cost, for example, of replacing oil resources destined for fuel consumption could be estimated by the cost of restoring or compensating for the function loss. An estimation of the cost of replacing the depleted asset with a substitute providing the same or a very similar function enables the GPI to ensure that the consumption possibilities of future generations are unchanged. This is in accordance with the Fisherian tradition.

This thesis has focused closely on the replacement costs of renewable energy alternatives providing the same function as their depleted non-renewable alternatives. In fact, there are two alternative ways in which a replacement value of a non-renewable resource can be estimated, and neither is satisfactory. The approximate market value of the depleted non-renewable resources could be used, or the marginal discovery cost of the non-renewable resource could be harnessed. However, using a market value for the replacement cost assumes that this is an accurate representation of the true replacement cost. This approach takes the current generation's valuation of the depletion variable, which is unlikely to be the same as the true cost of establishing a renewable substitute with the same function. The marginal discovery cost approach also has flaws. Via this method, the replacement cost value is comprised of the extraction and development costs of finding the same type of resource. It is therefore purely an expression of the scarcity value of the non-renewable resource. This approach cannot ensure that future generations have access to the same level of consumption opportunities as the current generation. It is merely a method in keeping with the Hartwick Rule, ensuring that sufficient funds are set aside so that further depletion of non-renewable resources can occur in the future.

This thesis has contended that it is more appropriate for the GPI to deduct the full costs of replacing a non-renewable resource with a renewable substitute. As Chapter 3 demonstrated, it is important to maintain consistency with the Fisherian tradition, and thus the substitute resource must be able to produce the same future income stream (service) as the depleted non-renewable resource did. This approach maintains consistency with both Fisher's notions of income and capital, and strong sustainability leanings in terms of the GPI's cost deductions. However, its application is not without practical difficulties. It can be complicated to determine the most appropriate renewable fuel substitute and what the costs of this resource might be. Oil, for example, which is mainly used as a transport fuel in the country of Iceland, could be replaced partially or entirely with biofuel production, or hydrogen, or indeed electricity if there was an expansion in the alternative vehicular industry. As Chapter 3 explored, academia has generally assumed rising prices for renewable fuels (3% per annum from a starting value of US $75, 1988 prices), using the same scarcity logic as would be applied to the non-renewable resource. Overall, this approach is highly illogical and acts as a disincentive for policymakers to encourage the wider use of biofuels, since the costs of non-renewable resources have not risen by more than 3% to reflect their increased scarcity. Recent estimates suggest that the costs of biofuels are falling and set to reduce further over the course of the next decade, subject to the consumption preferences of future generations.

Although it is easy to assume that renewable energy costs will continue to fall, at the same time many of the renewable energy resources might be competing with other resource functions. Crop-based biofuels, for instance, are frequently competing with available land for food production, or the best locations for onshore wind turbines might become exhausted. However, at the present moment, there are a number of renewable energy sources which could be used to replace depleted non-renewable energy resources. The costs of these resources will vary from location to location and from one generation to the next. In order to maintain the relative simplicity of calculating the GPI, this thesis has argued in favour of using the current market costs of the most probable renewable energy fuel alternative, evaluating heat and electricity generation separately. A major argument against this approach is that the performance and efficiency of the next best renewable alternative will vary from scenario to scenario, and thus a generic substitute can never truly replicate the functionality of the non-renewable resource. The greatest counterbalance to this weakness is the advantage that the replacement cost method embraces a strong sustainability perspective, signalling the importance of preserving natural capital stocks.

It is possible to argue that the robustness of the replacement cost method advised in this thesis is perhaps weakened by evidence of falling renewable energy costs. Applying the current market cost of renewable energy as the most suitable alternative to non-renewable resources looks like it will lead to lowering GPI cost deduction values over time. This is despite the fact that the scarcity value of non-renewable resources has increased over the same period of time. This argument misunderstands the GPI's message, which is not concerned with the accuracy of the costs of non-renewable renewable resource utilisation, only their finite nature, and the replacement costs of the alternative renewable resource. Where the costs of renewable fuel alternatives fall and non-renewable resource GPI cost deductions are thus lower, the eventual GPI per capita outcome will be higher, all other factors being equal and assuming the same level of non-renewable resource consumption is compared from one year to the next. Thus, the GPI acts as an incentive for policymakers to further invest in the renewable fuel market, driving these costs down even more. However, care still needs to be taken to ensure that the replacement cost value for renewable fuels does not send the wrong signal in the GPI concerning the sustainability of current economic welfare. One could argue that where there are falling renewable fuel costs and fixed levels of non-renewable resource utilisation over time, the increasing GPI per capita value is not reflecting an increase in the sustainability of economic welfare. Rather, it is showing an increase in the prospective nature of economic welfare, since it is easier to make the transition to a renewable energy future, but the current situation remains as reliant on non-renewable resources as it was before.

Finally, this thesis has contended that the replacement costs of non-renewable resource utilisation should be expressed as a function of utilised energy, not extracted. Using figures based on energy consumption means that it is not the extraction of fossil and nuclear fuels that is taken into account, but the consumption of these resources. The alternative approach of using the domestic extraction of non-renewable energy resources is flawed as it does not reflect the useful stream of services enjoyed in current time terms. If extraction exceeds use, then the GPI will significantly overestimate the replacement cost deduction.

## 5.2 Accounting for Unsustainable Renewable Energy Utilisation

### 5.2.1 Establishing $E_0$ and Legislative Issues

Existing GPI methodologies have assumed that the consumption of renewable energy represents the generation of sustainable economic welfare across generations. Chapter 4 of this thesis set out to show that the nature of renewable energy is often misconceived, and in a local context its 'renewable' credentials are decidedly uncertain. This is particularly the case with geothermal energy resources. Drawing upon the most up-to-date understanding of what constitutes the sustainable utilisation of geothermal resources and analysing four possible modes of production, a methodology for applying cost deductions to the GPI was outlined. Where geothermal power plants are producing at a level E above the sustainable level, $E_0$, the GPI should apply cost deductions for the excess energy generation in terms of the most suitable alternative resource and its particular LEC.

Chapter 4 included a speculative case study concerning the likely impact of this methodology on an estimated Icelandic GPI calculation. A mean 1.01% reduction in private per capita consumption was estimated. The main barrier to the practical application of the theory in this thesis is not the absence of a published Icelandic GPI calculation. Far from it, the deficiency lies in an absence of data concerning the sustainable production level at Icelandic geothermal power plants.

The analysis in Chapter 4 needs to be supported by ideas of how to embed the importance of the sustainable utilisation of geothermal resource into legislative processes. At present, as project planners tend to evaluate the likely success of power plants in purely economic terms across a 30 year period, there is little incentive to conceive of the need for a 100 year period of sustained energy production that accords with an intergenerational perspective. The current emphasis is one of maximising economic returns now, not sustaining the stream of energy consuming opportunities into the distant future. Indeed, there is an inherent conflict between the aim of maximising relatively short-term economic returns and ensuring the longer-term sustainability of the geothermal resource. In addition, the value for $E_0$ has been assumed to be fixed. In practice the sustainable level might well be expected to increase over time through technological advances (for example, deeper drilling) and increased reinjection. The definition for $E_0$ is simply one that accords with the intergenerational component of the GPI and ensures a stable stream of consumption opportunities.

Of the four modes of geothermal production discussed by Axelsson (2010), modes (1) and (2) are in accordance with the strong sustainability approach; modes (3) and (4) are representative of weak sustainability. Where geothermal systems are utilised in accordance with modes (3) and (4), other geothermal fields need to be available in the locality for utilisation whilst the former system is resting and replenishing. Thus, it could be argued that the overall production of the geothermal resource, across a given region, is sustainable. However, in terms of the GPI, this understanding is ignorant of the nature of current sustainable economic welfare. The utilisation of the geothermal resource in terms of its current output cannot be sustained for a period of 100 years, and thus the surplus output beyond $E_0$ is unsustainable.

It is possible, indeed essential in order for this thesis to have a practical application, for the legislative system to embed strong sustainability parameters into its permitting stipulations. Ketilsson et al. (2010) provides a general discussion of the means by which standard reservoir engineering tools can be forged into the permitting and legislative process accompanying decision making in geothermal projects. The authors envision two permitting categories, one for new projects and another for the expansion of existing plants. Although it is not common for projects to calculate their generating capacity over a 100 year timespan, existing methods could be used to create a best practice estimate. Simple methods based on surface and sub-surface exploration can glean valuable data concerning the system structure, chemistry of fumaroles, deep reservoir temperatures and fluid quality. Based on this data, a volumetric generating capacity estimate can be established, and this analysis can be refined via reference to the productive capacity of similar reservoirs elsewhere (Sarmiento and Björnsson, 2007). However, any estimate of $E_0$ at the pre-production stage will incorporate an error margin as pressure drawdown data will be missing and further resource discoveries may be made in the future (Ketilsson et al. 2010). There is thus the risk that the model to generate $E_0$ is an underestimate of the true sustainable production level, however, even so, it should be considered the maximum allowable production level permissible by national energy authorities. This situation could be resolved via independent re-evaluations of the sustainable level of production, perhaps occurring on an annual basis. Regular periods of review also provide power plant owners with the opportunity to optimise production over time and take advantage of emerging technological enhancement opportunities.

Where geothermal power plants are aspiring to expand production, it is much easier to establish the sustainable level of production. Established production fields will have detailed well by well numerical models considering prediction times for much longer than a 30 year period of economic maximisation (Ketilsson et al. 2010). Furthermore, the data is more accurate as pressure drawdown and recharge information is available. Sufficient information is available to make sure that the geothermal field adheres to the 100 year criterion for sustainable utilisation.

As it is relatively straight-forward to at least estimate a value for $E_0$, it is important to consider why this is not already a common requirement for new and expanding geothermal power plants. The answer is most probably that the process of legislative decision-making is clouded by political influence. Particularly in Iceland, where much of the electricity production from geothermal fields is destined for use in heavy industry projects, the economic benefits of overproduction outweigh sustainable utilisation concerns. Sustainability is a broad concept involving the reconciliation of competing economic, environmental and social objectives – it is not, in itself, concerned with the sustainability of economic welfare, unlike the GPI. Larger power projects are more likely to demonstrate production in line with modes (1) and (2) (Ketilsson et al. 2010). Rather than approving such projects irrespective of their sustainable utilisation credentials, regulatory authorities should instead strive to direct capacity support (finance, manpower, technology etc.) to try and raise the initial level for $E_0$ above its initial estimate. However, for clarity, the possibility of raising the level $E_0$ in the future is no justification for unsustainable levels of production in the early phases, and the GPI should deduct an appropriate cost if this approach is followed.

In the coming years, the development of a Sustainability Assessment Protocol for Geothermal Utilisation (GSAP) will be tested and implemented for projects in Iceland and further afield. Assuming widespread adoption over time, the GSAP should at least help to popularise the importance of maintaining sustainable yields from the geothermal resource.

### 5.2.2 The Use of LEC Methodology

This thesis has proposed the use of LEC methodology to calculate the costs of the unsustainable utilisation of geothermal resources in a current time period and in terms of the costs of the alternative energy asset providing the same or very similar function as the geothermal resource. The use of LEC methodology is particularly useful for a current measure of economic welfare such as the GPI, since it gives a present value of the costs of energy production.

This thesis has used national LEC averages to determine the likely costs of unsustainable geothermal utilisation in Iceland. While this is a reasonable premise to illustrate a theory, in practice the method is much more robust if plant specific data is applied. Even so, great care needs to be taken when comparing different LCE studies as the cost outcomes are highly dependent on the choice of discount rate, cost assumptions and capacity factors. For instance, although geothermal power generally has a capacity factor of upwards of 90%, for hydro power this amount can vary from 35% to 90% depending on the power plant's specific location (World Energy Council, 2013). In terms of costs, different LEC assessments will include some values (for example, connection of the generating source to the transmission grid) and not others. When applying a LEC-based deduction to the GPI and using many different studies, care has to be taken to ensure that the same assumptions are applied throughout. It should be noted that this study has used LEC estimates which are purely based on market costs. Maintaining consistency with the ecological economics ethos underpinning the GPI's methodology should necessitate the use of full LEC estimates for renewable energy alternatives. Therefore, ideally, LEC estimates should incorporate costs for socio-environmental damages, such as carbon dioxide emissions or air pollution. If this was the case then subtracting a GPI cost for unsustainable geothermal utilisation would fully account for the full set of anticipated socio-environmental impacts stemming from the substitute energy resource. Plant specific publications of LEC estimates incorporating the costs of socio-environmental impacts are very rare, although the 'External Costs of Energy' (known as ExternE) Project by the European Commission has calculated environmental external costs from various forms of renewable energy production (Krewitt, 2002). As yet, studies have been hampered by data shortages and focused on predominantly the economic costs of air pollutants, and no estimates have been carried out in Iceland on either their hydro power or geothermal power plants (Krewitt, 2002). However, there is the future potential for the ExternE methodology to be expanded to include other externalities and be of use when calculating the most appropriate GPI cost deduction for the unsustainable utilisation of geothermal resources.

It is also important to note that LEC estimates are typically based on 20 to 40 year timescales. Thus, the LEC appraisal takes place over a period where the economic feasibility of a power plant is considered, not a 100 year sustainability perspective. However, although this is apparently a methodological flaw, this is not necessarily the case. To understand this, it is important to hark back to the replacement cost approach recommended for non-renewable resources. The essential issue was establishing the market costs of the alternative renewable resource providing the same function. The same need applies here. The GPI needs to deduct the replacement market costs of the unsustainable component of geothermal utilisation, expressed in current time terms. The current market costs, expressed in terms of the average cost over the lifetime of a replacement geothermal (or alternative) plant, can only be considered in the light of the likely useful economic lifespan of the replacement plant. Even though LEC estimates for geothermal projects ignore sustainable utilisation issues, they remain the most accurate means of determining the current market costs of renewable energy production. Until the market perspective shifts to viewing geothermal production over a 100 year timescale, the LEC estimates will remain somewhat higher.

### 5.2.3 Geothermal Energy and Other Economic Welfare Impacts

This thesis has focused almost entirely on the economic welfare impacts of unsustainable energy utilisation. It has therefore tended to assume that the remainder of the GPI captures costs (and the correct costs) for all of the negative environmental impacts stemming from renewable energy use. The GPI is not necessarily designed to be an all-encompassing metric of sustainable economic welfare – measuring this would be impossible – but it should strive to capture the predominant influences. In the most part, it does so. However, if one focusses once again on the case of geothermal resources in Iceland, there are many possible economic welfare costs that are not typically embraced by the GPI. Stefánsdóttir (2011) has compiled a list of the main environmental impacts not accounted for within the GPI methodology:

1. Land subsidence and earthquakes – when fluid and steam from underground reservoirs is extracted there is a possibility of land subsidence due to the sinking of the reservoir. This presents the risk of damage to local infrastructure and the sustainability of power production. This risk is also present when considering the need to re-inject geothermal fields to maintain a high level of production. Reinjection, particularly at Hellisheiði, has been found to be a trigger of many small earthquakes in the region.
2. Ecosystem impacts in geothermal reservoirs – geothermal reservoirs are typically home to special ecosystems where rare, heat-resistant microorganisms thrive. These reservoirs need to be defined and captured within the wetland loss cost category.
3. Direct impacts on terrestrial ecosystems – flora and fauna in the vicinity of geothermal power plants may be destroyed.
4. Chemical or thermal pollution – discharged water from geothermal power plants will lead to an increase in the temperature of surface water environments. This increase will have impacts on the ecosystem, benefiting some species and negatively impacting others.

5. Visual pollution – geothermal power stations often present a form of visual blight to surrounding localities, potentially discouraging tourism and leisure activities.
6. Noise pollution – it is important that the noise cost deduction incorporates specific emissions from geothermal power plants. Geothermal power production creates high-pitched noise emissions when steam travels through pipelines and other emissions occur via the cooling towers and steam ejectors.
7. Conflicts with cultural and archaeological features – the land used to build up plants can be of cultural or archaeological importance, and assets of historical value may be lost or reduced in quality due to the installation of a geothermal power plant.

As there is no SNA for the GPI, assessors need to determine whether these negative features are of sufficient significance to merit inclusion in the calculation. In the cases of ecosystem impacts in geothermal reservoirs and chemical or thermal pollution, establishing a monetary valuation via Travel Cost and Willingness to Pay methodology would be very challenging. Although visual pollution has perhaps a more significant impact on the sustainability of economic welfare, it is important to consider whether the inclusion of an extra cost deduction equates to a double deduction. It would seem to be the case that the effect would lead to decreased consumption via a reduction in the demand for tourism activities. If this is so, an additional GPI deduction is unwarranted. With regards to possible damage caused by earthquakes and land subsidence, this cost needs to be incorporated within component 12 in Table 2.1 relating to defensive environmental measures. It is important to realise that the risk of land subsidence or earthquakes is not in itself deserving of a cost deduction in the GPI – the only issue that matters is if actual economic costs are incurred as a consequence of these events.

Another potential example of potentially unsustainable 'renewable' energy utilisation involves hydro power – a seemingly ubiquitous natural resource at the global level may be utilised unsustainably at the local level. Hydro power is considered a renewable energy resource because it uses the Earth's water cycle to generate electricity (MacKay, 2008). Local hydrological conditions therefore matter, and future flows of water along river courses or from glacial melting are not fixed constants. The depletion of the store of water in a dammed reservoir to generate hydroelectricity may or may not represent sustainable utilisation based upon the future characteristics of the water cycle. There is thus a seasonal value for sustainable production, but it is very hard to approximate with any certainty. Unlike the case with geothermal resources, where the heat flow through the Earth is reasonably constant, any estimation of the sustainable level of production for hydro power is fraught with technical difficulties and assumptions, and calculating a GPI cost deduction for unsustainable utilisation would be very difficult. It is not possible to state with any certainty that a significant depletion in the water store in year one represents sustainable or unsustainable utilisation, as the recovery depends on estimates for future rainfall or melt water accumulations. These can be approximated based on past trends, but are often very inconsistent on a year to year basis.

### 5.2.4 An Issue for the Icelandic GPI or Further Afield?

The use of an Icelandic case study in this thesis begs the question of whether unsustainable geothermal utilisation is an issue that only affects this nation and has an impact on its GPI. Ketilsson et al. (2010) contend that economic pressures leading to overproduction will occur in nearly every geothermal field used to source electricity. Projections by Goldstein et al. (2011) assert that by 2050 geothermal energy could meet 3% of global electricity demand (it was 0.1% in 2008) and 5% of global heat demand by 2050. Currently, in addition to Iceland, the countries of The Phillippines (27.00%), El Salvador (25.00%), Costa Rica (14.00%), Kenya (11.20%), New Zealand (10.00%) and Nicaragua (10.00%) all generate a significant proportion of their electricity from geothermal resources (Matek, 2013). Of these nations, currently only New Zealand has calculated their GPI, although evidently if accounts were formed for other nations with a significant geothermal aspect to their electricity composition, they will need to consider sustainability utilisation issues. New Zealand's GPI was US $16,400 per capita in 2010 at 2005 prices (Kubiszewksi et al., 2013). The total installed capacity in geothermal power plants is 895 $MW_e$ (Matek, 2013), equating to maximum production of approximately 7,840,200 MWh per year. Applying a very arbitrary assumption that 20% of total production represents unsustainable utilisation and assuming that there are replacement geothermal fields for utilisation as substitute energy assets, 1,568,040 MWh of electricity output is unsustainable. As per the Icelandic case study, by taking a 2005 LEC global average estimate of US $54.49 (2005 prices) for geothermal flash plants, a total cost deduction of US $85,442,500 should be applied to New Zealand's GPI. As New Zealand's population was approximately 4,027,947 in 2010 (Statistics New Zealand, 2014), on a per capita basis, New Zealand's 2010 GPI should deduct US $21 for the unsustainable utilisation of geothermal resources, a 0.13% subtraction from its current GPI.

The example of the New Zealand GPI highlights a potential limitation in the applicability of the methodology proposed in this thesis, as well as a possible reason why this issue has not been considered in other national studies. Unlike in Iceland, which has a low population and considerable geothermal utilisation for energy intensive industrial projects, New Zealand's electricity output from such sources is dispersed amongst a population of over 12 times the size. Although in total installed capacity terms, New Zealand has 25.81% more geothermal resources producing electricity than Iceland (Matek, 2013), its GPI deduction is negligible in comparison. It may be the case, therefore, that although the sustainability of renewable energy yields is an important determinant of economic welfare, in terms of the GPI the impact of unsustainable practices is insufficient to even merit its inclusion in the calculation methodology for many nations. Certainly it is possible to consider that nations with less than 10% of their electricity supply from geothermal resources might want to overlook this issue in favour of preserving the straight-forwardness of the calculation method.

An ultimate aim for the GPI is for it to become a tool that can easily analyse public policy, and the act of doing so should not be hindered via the need to calculate many relatively insignificant components of sustainable economic welfare. Instead of quantifying economic impacts in terms of traditional accounting measures, such as GDP, the GPI should be able to easily assimilate the welfare benefits and costs of policy changes. However, in the case of a country such as Iceland, the GPI accounting methodology should include a component related to the unsustainable utilisation of geothermal resources. Suppose the Icelandic government decided to exploit the remaining 15.3 TWh of exploitable geothermal resources for electricity generation. The GPI would show many benefits in consumption terms, both in terms of energy usage itself and via induced income for domestic households employed in the construction projects for the new power plants. However, the Icelandic GPI should be able to show all of the major costs too, including increased carbon dioxide emissions, air, water and noise pollution, vulnerability to foreign loans financing the project, and the instigation of a potentially unsustainable energy resource.

The use of cost-benefit analysis to determine the desirability of various government policy initiatives reinforces the notion that the GPI measures weak sustainability. Overall, this is undeniable, as the benefits of increased energy consumption are weighed up against their many costs. This is embedded substitutability as gains in current economic welfare are allowed to persist provided they exceed their costs. However, as this thesis has reiterated, it is from a cost perspective that strong sustainability ideals are reflected in the GPI. Where natural capital resources are permanently destroyed, or indeed welfare gains cannot be sustained over an intergenerational period, the GPI recognises this. Looking forward, the main task for GPI practitioners appears to be one of refining the methodology to ensure that all of the main aspects influencing economic welfare are captured using the most appropriate methodology.

## 5.3 Thesis Limitations and Further Research

The theoretical advancements to the GPI's methodology for the unsustainable utilisation of renewable energy resources have been focused entirely on geothermal resources. There are three main reasons for this: a) the availability of an existing framework for measuring unsustainable levels of geothermal utilisation, b) anecdotal evidence of unsustainable patterns of utilisation, and c) the author's study location. This thesis does not, therefore, provide a means of calculating GPI cost deductions for all renewable energy resources that are utilised unsustainably. For example, the recommended cost method for unsustainable geothermal utilisation is ill-equipped to address declining yields from either biomass or hydro power production. Future research could be focussed on developing GPI cost deduction methods for other, purportedly renewable technologies.

Although methodologically robust in terms of the GPI's strong sustainability vision, the GPI cost deductions calculated for Iceland have been somewhat arbitrary estimates. Until the sustainable level of production is known across all Icelandic geothermal power plants, it is only possible to estimate the unsustainable proportion of production. The acquisition of this data may be neither nor popular from a political perspective, since policymakers tend to encourage the maximisation of economic returns from energy production over the maintenance of sustained yields. However, in order for the GPI to truly capture the major facets comprising economic welfare, future research undoubtedly needs to discover sustainable levels of production across all high-enthalpy geothermal fields, commencing in Iceland with those power plants producing electricity to serve heavy industry. Once this data has eventually been acquired, the next step in transforming theory into practice would be to apply this thesis' recommended cost deduction methodology to all countries harnessing geothermal resources and seeking to conduct a GPI calculation. The true economic extent of unsustainable geothermal utilisation, relative to the GPI's starting point of private consumption levels, can then be established. Subsequent research would then need to focus on ensuring that the full LEC of the substitute renewable energy resource was applied to the GPI cost deduction, rather than the current dominance of market-based calculations, which overlook the importance of costing externalities.

# 6 Conclusion

As the global depletion of finite non-renewable resources has increased and the state of the environment deteriorated, there has been a palpable increase in interest in the role of natural capital resources. Chapter 2 of this thesis began by highlighting the one-dimensional treatment of non-renewable resource depletion in the SNA and its ultimate statistic, GDP. This thesis proceeded to examine the extent to which alternative measures of economic welfare to GDP accord with the strong and weak sustainability paradigms. Over time, the focus of such measures has gradually shifted from defining the optimal depletion rate of non-renewable resources towards defining the conditions necessary for sustainable economic welfare. One such condition is intergenerational equity, a requirement for non-declining consumption across generations. In the GPI – the most evolved measure of sustainable economic welfare – an essential tenet is the maintenance of a fixed stream of private consumption across generations, while at the same time the welfare diminishing consequences of economic activity should be minimised. The GPI's cost deductions incorporate the importance of shifting from the utilisation of finite non-renewable resources for energy consumption to increased usage of renewable sources. The GPI thus sits in contrast to preceding and alternative measures of economic welfare examined in this thesis (for example, the NDP, MEW and SMEW), which are much more symbiotic of the weak sustainability paradigm, tending to place considerable emphasis on the substitutability of capital classes.

Conventional national accounting frameworks have resulted in misplaced signals concerning the depletion of natural capital stocks. The political litmus paper of economic growth is illusory in the sense that the liquidation of environmental assets is registered as income. This thesis provided a comprehensive review of ways in which costs for the utilisation of non-renewable resources can be incorporated into the GPI's accounting methodology. The main conceptual basis behind the replacement cost approach is sound, and certainly more appropriate from a strong sustainability perspective than the oft-mooted El Serafy user cost approach. In addition, this thesis has contended that the methodologically correct approach is to deduct the full rather than partial replacement cost of the most probable renewable energy fuel alternative, assessing electricity and heat generation separately. Although the partial replacement cost method has been advised by Neumayer on the grounds of the future availability of non-renewable resources for utilisation, this thesis argued that such an approach violates the GPI's intergenerational ideology. The GPI is not merely concerned with the sustainability of economic welfare next year, but across generations. This thesis has considered the technical complexities and inherent weaknesses in the replacement cost approach. It is a necessary but difficult task for national or regional GPI assessors to establish the most feasible renewable energy alternative in barrel of oil equivalent terms. In reality, a range of different renewable energy fuels could be (and of course are) used as substitutes for fossil and nuclear fuel consumption.

Chapter 4 moved beyond a mere justification and refinement of existing theories, and highlighted the importance of considering the nature of the renewable energy alternative. Although in most cases renewable resources demonstrate sustainable levels of utilisation and reliable yields over an intergenerational timespan, this is frequently not the case with geothermal resources, especially where high-enthalpy fields are used for electricity production. Rates of pressure and temperature replenishment tend to be very slow, while economic demands lead to geothermal resources being extracted with unyielding avarice. Starting with Axelsson's (2010) model of sustainable geothermal production and then highlighting different potential modes of production, Chapter 4 delved into existing case studies from Iceland, the United States and New Zealand. These showed production patterns that generally exhibit weak sustainability behaviour, with replacement assets needed to top up declining capacity well before a 100 year period has passed. Failing to maintain a sustainable level of production is, in terms of the GPI, an indicator of an unsustainable level of economic welfare. Although geothermal resource owners consider profitability over roughly a 30 year timescale, the GPI's embedded intergenerational principle requires a far-distant perspective.

This thesis proposed that the unsustainable element of current geothermal production – defined as the difference between current output and the theoretically sustainable level – should lead to the appropriation of costs in the GPI calculation methodology. These deductions are referred to as the 'unsustainable utilisation of 'renewable' resources', an oxymoron of sorts. The costs are calculated through the use of LEC estimates for the most suitable alternative energy asset to cover the gap between the current and sustainable level of geothermal production. The most probable alternative energy asset will be a nearby geothermal field, although it is recognised that in the case of Iceland, hydro power might be used too. Using the example of Iceland, an arbitrary 20% level of unsustainable geothermal utilisation and many other assumptions, it is estimated that a cost reduction equal to 1.01% of Iceland's 2013 value for private consumption (US $21,978, PPP, 2005 prices) should be applied, leading to a derived final GPI per capita figure of US $12,259 (PPP, 2005 prices). Chapter 5 of this thesis considers the main steps necessary to move the embryonic theories in this thesis into practice. In summary, these are:

- For all geothermal power plants, the sustainable level of production, $E_0$, needs to be independently estimated, and permitting applications for new and expanding projects should demand this information to ensure that strong sustainability principles are integrated into legislative processes. This need could be partially satisfied via the popularisation of the GSAP.
- Governments should undertake necessary investments to try and raise the sustainable level of production, $E_0$, from the initial estimate. This approach leads to burgeoning energy consumption opportunities for society, and helps to maximise the relatively short-term goal of profit-maximisation demanded by geothermal resource owners.
- LEC data for replacement energy assets should be extracted from national and regularly updated databanks, wherever practicable.
- GPI assessors need to carefully evaluate the most suitable replacement energy asset for unsustainable geothermal production, and the most likely option may differ according to whether the function of heat or electricity production applies.

It is important to reiterate that the GPI is only a measure of sustainable economic welfare in current terms, although it is evident that its many cost deductions largely assimilate the energy sustainability credentials of renewable resources, particularly with regards to their environmental impacts. However, the GPI is in fact far from all-encompassing in terms of its depiction of economic welfare. When considering geothermal energy production, the GPI rewards the process of reinjection in the sense that energy consumption opportunities are maximised, or at least maintained over a longer period. However, the negative consequences in terms of economic welfare are likely to be glossed over via the adoption of a typical GPI methodology. As Chapter 5 of this thesis explored, some issues connected to geothermal energy exploitation that are not generally considered by the GPI include land stability and earthquakes. It is therefore essential that any national (or regional) GPI study fully reviews all sources of current economic welfare, and then adopts an appropriate methodology. At the very least, this thesis has demonstrated that a future GPI methodology for Iceland should consider the sustainable utilisation of geothermal resources. This nascent research could eventually act as a steering point for other nations exploiting significant geothermal resources and seeking to carry out a GPI calculation. The decision to include this cost component or not will depend on how keen a GPI assessment team are to veer from a relatively straight-forward calculation methodology, and indeed whether an international zeal emerges to appraise the sustainable utilisation of all geothermal resources.

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