Promoting environmental sustainability through the utilisation of an indicator set, ecosystem services perspective and non-market valuation techniques

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Dissertation submitted in partial fulfilment of a *Philosophiae Doctor* degree
in Environment and Natural Resources

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Abstract

Enhanced understanding and knowledge concerning a nation's environmental sustainability performance is necessary to ensure the long-term flourishing capacities of economies and critical to the maintenance of human well-being, particularly through the provisioning of multiple ecosystem services. The case study of Iceland is referenced throughout this thesis to explore linkages between environmental sustainability impacts at a national level with environmental and ecosystem service impacts occurring on a project-specific basis, particularly those associated with energy developments.

Paper I of this thesis uses the case studies of Iceland and Norway to outline a new methodology for selecting indicators of environmental sustainability specific to the national context. Following a series of focus groups, expert judgment was applied as part of a five-stage process leading to the selection of 23 indicators from an initial pool of 30 possibilities. Easy-to-understand evaluative techniques, in the form of radar charts and traffic-lights, were used to appraise national progress in relation to targets and trend-based objectives respectively.

Paper II considers the project-specific nature of environmental impacts in the Icelandic energy sector. On the basis that determining the acceptability of environmental impacts can become a subjective affair skewed by vested interest, an argument is set forth for the use of non-market-valuation techniques to account for environmental costs. This paper discusses the way in which utilitarian values of the environment could be incorporated into the existing decision-making and regulatory apparatus for Icelandic energy projects.

Paper III then focuses directly on geothermal energy in Iceland, using an ecosystem services perspective to highlight typical impacts to the quality and quantity of their provisioning through the development of a high-temperature power project. The first thematic classification of ecosystem services in a geothermal energy context is outlined using the Common International Classification of Ecosystem Services (CICES) framework. A

pluralist approach is advocated to account for the diverse range of utilitarian and intrinsic values typically associated with geothermal areas.

Paper IV reports on the results from the first two contingent valuation studies in Iceland – on Eldvörp and Hverahlíð – aimed at (a) eliciting preferences for the preservation of high-temperature geothermal fields, and (b) estimating willingness to pay for their preservation. The estimated mean willingness to pay for the preservation of Eldvörp and Hverahlíð is 8,433 ISK and 7,122 ISK respectively.

A similar methodology is also applied in Paper V to estimate the economic value of preserving Heiðmörk, a popular recreational area of green open space located on the fringes of Reykjavík, Garðabær and Kópavogur. The welfare estimates provide evidence that Icelanders consider Heiðmörk to possess considerable total economic value, with taxpayers willing to pay in the range 17,039 to 24,790 ISK per payment to secure its preservation.

This thesis draws attention to the need for Iceland to gain further knowledge about the economic value of its diverse landscape types. Future research should focus on the practical deployment and uses of the environmental sustainability indicators, and the creation of a framework for the spatial mapping and economic valuation of Iceland’s ecosystem services, both from the perspective of the producer and consumer.

Útdráttur

Umhverfisleg sjálfbærni er forsenda þess að hagkerfi þjóðar þróist með farsælum hætti. Það er því mikilvægt að þekkja og skilja hvernig þessum málum er fyrirkomið hjá einni þjóð, ekki síst með tilliti til þess hvað framlag náttúrunnar (e: ecosystem services) er mikilvægt fyrir velsæld manna til langs tíma litið.

Þessi ritgerð byggir að mestu á tilviksrannsókn á Íslandi þar sem greind eru frá ýmsum sjónarhornum tengsl umhverfislegrar sjálfbærni á landsvísu við áhrif orkuvinnsluframkvæmda á náttúrgæði.

Fyrsta grein ritgerðarinnar byggir á tilviksrannsókn með samanburði á Íslandi og Noregi, þar sem lýst er nýrri aðferðafræði við val á vísum til að meta umhverfislega sjálfbærni á landsvísu. Eftir hópviðtöl var fimm þrepa aðferð beitt til að velja 23 vísa af þeim 30 sem lagðir voru fram í upphafi rannsóknar. Auðskiljanlegum aðferðum, svo sem geislagröfum og umferðaljósakerfi var beitt til að greina og kynna stöðu viðmiða í löndunum tveimur.

Grein tvö fjallar um umhverfisáhrif virkjanaframkvæmda. Þar sem hagsmunir geta haft áhrif á viðhorf til umhverfisáhrifa virkjanaframkvæmda er lagt til að verðmætamat sé notað til að meta kostnað umhverfisáhrifa. Greinin fjallar um hvaða verðmæti gætu verið tekin til greina í slíku mati, og sömuleiðis við stjórnsýsluákvarðanir tengdar virkjanaframkvæmdum.

Þriðja greinin fjallar um jarðvarma á Íslandi og áhrif virkjanaframkvæmda á möguleika náttúrunnar að veita vistkerfisþjónustu eða náttúrugæði. Kynnt er fyrsta flokkun náttúrugæða í tengslum við jarðvarma, þar sem byggt er á ramma “the Common International Classification of Ecosystem Services (CICES)”. Lögð er áhersla á að beita fjölbreyttum aðferðum til að nálgast hin margvíslegu náttúrgæði sem tengjast jarðvarmasvæðum.

Í fjórðu grein er beitt skilyrtu verðmætamati á tveimur jarðvarmasvæðum, Eldvörpum og Hverahlíð. Markmið rannsóknarinnar var að a) greina vilja almennings til að vernda þessi svæði, og b) að meta vilja manna til að greiða fyrir slíka vernd. Niðurstöður sýna að greiðsluvilji fyrir vernd Eldvarpa var að meðaltali 8.433 kr og 7.122 kr fyrir Hverahlíð.

Grein fimm byggir á sömu aðferðafræði þar sem metinn var greiðsluvilji til að vernda Heiðmörk. Heiðmörk er vinsælt útivistarsvæði í nágrenni Reykjavíkur, Garðabæjar og Kópavogs. Skattgreiðendur reyndust tilbúnir til að greiða frá 17.039 kr til 24.790 kr til að tryggja vernd Heiðmerkur.

Ritgerðin í heild sýnir mikilvægi þess að Íslendingar auki þekkingu á virði náttúrugæða landsins í mismunandi vistgerðum og landslagi. Frekari rannsóknir ættu að beinast að hagnýtingu umhverfisvísa, og að mati á landfræðilegu virði náttúrugæða Íslands, bæði frá sjónarhorni neytenda og framleiðenda.

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Finally, I would like to commend the support of my mother and various friends, encouragement which has been invaluable in ensuring the progression of the thesis to the stage of completion.

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List of Papers

This thesis is based on five published papers, which will be referred to in the text as the following chapters:

Paper I: Chapter 2
Cook, D., Saviolidis, N. M., Davíðsdóttir, B., Jóhannsdóttir, L., & Ólafsson, S. (2017). Measuring countries' environmental sustainability performance – The development of a nation-specific indicator set. *Ecological Indicators*, *74*, 463-478.

Paper II: Chapter 3
Cook, D., Davíðsdóttir, B., & Kristófersson, D. M. (2016). Energy projects in Iceland–Advancing the case for the use of economic valuation techniques to evaluate environmental impacts. *Energy Policy*, *94*, 104-113.

Paper III: Chapter 4
Cook, D., Davíðsdóttir, B., & Kristófersson, D. M. (2017). An ecosystem services perspective for classifying and valuing the environmental impacts of geothermal power projects. *Energy for Sustainable Development, 40*, 126-138.

Paper IV: Chapter 5
Cook, D., Davíðsdóttir, B., & Kristófersson, D. M. (2018). Willingness to pay for the preservation of geothermal areas in Iceland – the contingent valuation studies of Eldvörp and Hverahlíð. *Renewable Energy, 116*, 97-108.

Paper V: Chapter 6

Cook, D., Eiríksdóttir, K., Davíðsdóttir, B., & Kristófersson, D. M. (2018). The contingent valuation study of Heiðmörk, Iceland – willingness to pay for its preservation, *Environmental Management*, *209*, 126-138.

1. Introduction

1.1 Research focus and structure

This thesis explores links between environmental sustainability issues on a nation-state scale with environmental and ecosystem service impacts at the project-specific level, particularly focused on those connected to energy projects. The research has an interdisciplinary focus and addresses connected objectives in the following chronological order: (1) developing a method for measuring the environmental sustainability performance of nations using an indicator set; (2) providing a review of the decision-making framework in Iceland connected to energy projects and accounting for environmental impacts; (3) conducting the first thematic review of ecosystem service impacts connected to the development of high-temperature geothermal power projects; (4) applying the contingent valuation method to research preferences and estimate willingness to pay for the preservation of the geothermal fields, Eldvörp and Hverahlíð; and (5) applying the contingent valuation method to research preferences and estimate willingness to pay for the preservation of Heiðmörk, an urban park on the edge of Reykjavík.

This thesis commences in Paper I by proposing a methodology for selecting suitable indicators of environmental sustainability in a national context, drawing upon the case study examples of Iceland and Norway. In recent years, there have been relatively few advancements in measuring environmental sustainability at the nation-state scale, not least due to the difficulties in obtaining up-to-date, nation-specific and high quality data. The paper by Olafsson et al. (2014) is perhaps the only recent publication to take on this task, using the case study of Iceland to review the effectiveness of existing environmental indices[1] in capturing the multiple dimensions of environmental sustainability. In particular, this work involved a detailed examination of the environmental impacts deriving from Iceland's increased utilisation of renewable energy these past few decades. The authors discovered that the wider health and long-term environmental sustainability implications of Iceland's renewable energy utilisation – for example, the hydrogen sulphide and particulate matter concentrations associated with increased use of geothermal energy for electricity generation – were not calculated within any of the international indices. Some aspects of significant importance to Iceland's environmental sustainability performance were simply not mentioned at all – for example, in the case of

[1] These included the Environmental Vulnerability Index, Environmental Performance Index, Happy Planet Index and Ecological Footprint.

soil erosion – or assessed against inappropriate targets – for example, in the Environmental Performance Index, the use of a 1990 baseline as a basis for appraising Iceland's afforestation performance. Briefly, in the discussion section of this review article, the authors scoped out a potential framework for developing a set of indicators capable of capturing the multiple dimensions of environmental sustainability in a national context. However, the methodology for selecting suitable indicators of environmental sustainability, establishing relevant targets or trends, and how to graphically illustrate performance over time was not proposed.

Given the central role that energy projects play in determining a nation's environmental sustainability performance, particularly in Iceland, it is essential that environmental impacts are afforded sufficient arbitrage in decision-making, so as to avoid the potential for sub-optimal outcomes. In Paper II, this thesis analyses the body of institutions and regulations underpinning Icelandic decision-making for energy projects, reporting a 'regulatory gap' and proposing amendments to account for the economic value of environmental impacts. As has been observed by the OECD in their Environmental Performance Reviews of Iceland, in the absence of such accounting procedures connected to power projects, there is the potential for decision-making which is averse to the public interest.

Establishing knowledge about preferences and willingness to pay for the preservation of natural resources is critical in order to bridge the 'regulatory gap'. An ecosystem services perspective to analysing environmental impacts is helpful, as the concept is inherently bound to the promotion of human well-being. In Paper III, this thesis provides a general review of ecosystem services impacts connected to geothermal power, the first such study in the academic literature. Ecosystem service impacts are classified using the CICES framework, and then three criteria are applied to determine whether they ought to be valued using either monetary or non-monetary sources of information. Next, in Paper IV, the thesis reports on the case study outcomes from the contingent valuation studies on the geothermal fields of Eldvörp and Hverahlíð. Following the work of Thayer (1981), these are the second and third non-market valuation studies in the academic literature to estimate the economic value of preserving geothermal areas. The methods adopted and formation of total economic value estimates represent an approach that could be used in cost-benefit analyses for future Icelandic energy projects, ensuring that their economic welfare gains or losses were known. Finally, in recognition that environmental sustainability, ecosystem service and economic welfare impacts in Iceland can also derive from landscapes other than geothermal environments, this thesis reports in Paper V on the outcomes from the contingent valuation study of Heiðmörk, a popular forested area of parkland on the edge of Reykjavík. There is a very limited history in terms of conducting non-market valuation techniques in Iceland, and thus these papers represent the first steps in understanding preferences and willingness to pay for the preservation of different landscape types.

The remainder of this introductory chapter provides the reader with a general background to the issues discussed in subsequent chapters, which are formed of five academic papers. The main sub-sections are as follows. Section 1.2 defines and explains the environmental sustainability concept in a national context, including a discussion concerning the role of indicators in measuring national performance over a period of time. Section 1.3 provides a brief background to cost-benefit theory, specifically with reference to typical failures to account for ecosystem services impacts and the importance, from an economic welfare perspective, of valuing these. Section 1.4 reviews the concept of sustainable energy development and how Iceland has, in less than a century, transitioned from reliance on fossil fuels to the widespread use of renewable energy. The likely future trajectory for the utilisation of geothermal power projects is discussed. Section 1.5 provides a brief history of the practice of non-market valuation techniques in Iceland, whilst Section 1.6 discusses in detail the results from the one global study connected to the preservation of geothermal areas. Section 1.7 outlines in more detail the methods and research questions particular to each of this thesis' five papers.

1.2 Understanding and measuring environmental sustainability in a national context

1.2.1 Environmental sustainability and ecosystem services

A sustainable national economy relies heavily on the consumption of goods and services, but is ultimately dependent on the productive capacities of its natural resources (Morelli, 2013; Bolcárová and Kološta, 2015; Ciegis et al., 2015; O'Rourke and Lollo, 2015). In cases where economic advancement occurs without consideration of environmental sustainability issues, over time there is an increased likelihood of a diminishment in the vitality and productive capacities of a nation's land, oceans, freshwater systems and atmosphere (Bishop and Pagiola, 2012; Moldan et al., 2012; Olafsson et al., 2014). Often the economic advancement of nations occurs hand-in-hand with growth in energy consumption (Stern, 1993; Yang, 2000; Liddle and Lung, 2015).

The highly popularised Brundtland definition of sustainable development applies a three pillars approach to depict the interactions between economic activity, quality of life and the perpetuity of ecosystems and natural resources (Brundtland, 1987). Societies deficient in functioning life support systems cannot thrive, whilst an absence of supportive social structures and governance institutions prevents economies from flourishing. Often sustainable development has been interpreted as social and economic development that *should* be environmentally sustainable (Moldan et al., 2012). In recent, years there has been gradual acceptance that environmental sustainability has its own merits as a concept of primary focus (Jordan and Lenschow, 2014; Olafsson et al., 2014).

This thesis adopts the widely-cited definition of environmental sustainability set out by Goodland (1995). Environmental sustainability seeks to *"improve human welfare by protecting the sources of raw material used for human needs and ensuring that the sinks for human wastes are not exceeded, in order to prevent harm to humans"* (Goodland, 1995, p.3). This conceptualisation recognises implicitly that delivering environmental sustainability necessitates the placing of constraints on resource consumption, a central tenet behind the notion of 'limits to growth' found in the ecological economics framework (Olafsson et al., 2014).

In 2001, the OECD further advanced conceptual understanding by delineating four criteria and five complementary objectives for the delivery of environmental sustainability. The four criteria are:

(1) Regeneration – renewable resources shall be used efficiently and their use shall not be permitted to exceed long-term rates of natural regeneration;
(2) Substitutability – non-renewable resources shall be used efficiently and their use limited to levels which can be offset by substitution with renewable resources or other forms of capital;
(3) Assimilation – releases of hazardous or polluting substances into the environment shall not exceed their waste assimilative capacity;
(4) The avoidance of irreversibility. (OECD, 2001b, p.6):

Related to these criteria, the five objectives are: (1) maintaining ecosystem integrity via the efficient management of natural resources; (2) decoupling of environmental pressures from economic growth; (3) enhancing quality of life; (4) improving global interdependence by improving governance and co-operation; and (4) measuring progress, particularly using environmental indicators and indices.

The provisioning of ecosystem services at a given quantity and level of quality is intrinsic to environmental sustainability. Where Goodland defines environmental sustainability as partly relating to the prevention of harm to human beings, it is consequential that humanity must source well-being from its various ecosystems. This is the fundamental notion underpinning the ecosystem services concept. Furthermore, as the Millennium Ecosystem Assessment voiced, without ecosystem services, human economies or well-being cannot exist (MEA, 2005). The question for governance institutions and policy makers is what level of ecosystem services should be preserved – in quality and quantity – in order for human beings to source a level of well-being that is deemed satisfactory in the here and now, whilst not compromising the needs of future generations. Moldan et al. (2012) conclude that environmental sustainability may be defined simply as the maintenance of ecosystem services at a 'suitable' level. This requires ecosystem services across multiple spatial scales – local, regional, national and international – to be maintained in a healthy state, and also conveys a duty of care and monitoring obligations on behalf of governance institutions.

A further advantage of the ecosystem services perspective, in terms of promoting environmental sustainability, is its capacity to account for values, not merely describe the extent or quality of ecosystems (Jordan and Lenschow, 2009). It is through the valuation process that the full links between natural capital, ecosystem services and environmental sustainability are made apparent – it becomes even more evident that there is some quality or quantity that must be sustained over time in order to provision human well-being.

1.2.2 Use of indicators to measure environmental sustainability performance

Use of quantitative data and indicators to describe and measure environmental conditions in a national and international context is a well-established process. Indicators can be a very useful means of comprehending the environmental state of a nation (Heink and Kowarik, 2010; Dobbie and Dail, 2013), particularly connected to the impacts of energy use. There are a number of arguments in the academic literature promoting their use, including the monitoring of progress over time (Olafsson et al., 2014); communicating early warning information about the changing state of the environment (DANTES, 2003); evaluating the effectiveness of policies aimed at delivering a defined environmental outcome (DEFRA, 2003); and aiding decision-makers to take policy actions to improve outcomes (Devuyst et al., 2001). Indicators can thus play an important role in the policy cycle through the provision of information to support decision-making and regulatory progression (see Figure 1-1).

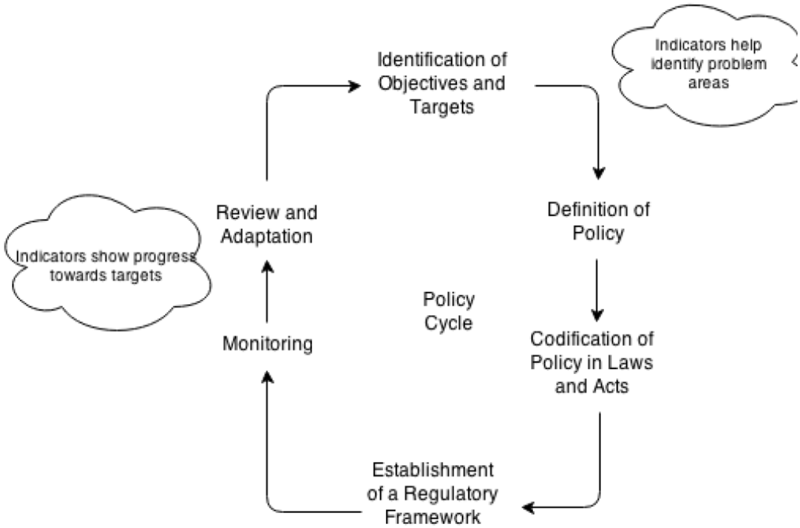

Figure 1-1: Role of indicators in the policy cycle, adapted from Shields et al. (2002)

Many individual energy indicators already exist, such as measures of reliance on renewable energy versus fossil fuels and emissions of various air pollutants. However, while energy indicators are very useful, they are unable to provide a holistic account of a nation's environmental sustainability performance, which necessitates the use of indicators across multiple environmental themes.

1.3 Cost-benefit analysis and valuing ecosystem service impacts

The objective of cost-benefit analysis is to quantify whether a development project can be expected to deliver greater net benefits (or 'welfare gains') than alternative options, including the scenario of not developing. Traditionally, economic analyses of the gains or losses of a project have been confined in cost-benefit analysis to the economic costs and benefits incurred directly due to development. Extended cost-benefit analysis also factors in indirect costs, particularly environmental impacts, which affect the quantity and/or quality of ecosystem services provisioned by natural resources.

Practitioners in the field of ecosystem services research usually use a classification framework for ecosystem service impacts in order to better interpret the land-use implications and trade-offs associated with development options. Many classifications exist, including those set out in the Millennium Ecosystem Assessment (MEA, 2005), The Economics of Ecosystems and Biodiversity (TEEB, 2010), and the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin, 2010). CICES is an attempt to standardise existing typologies, including the MEA and TEEB, and brackets ecosystem services according to whether they are of a provisioning, regulation and maintenance, or cultural type.

In many circumstances, markets provide an effective means of revealing preferences and values through decisions to buy and sell goods and services at certain prices. In environmental contexts, markets either do not exist or fail to fully reflect values, unless they relate directly to the buying and selling of a provisioned good such as felled forest timber. Normally ecosystem services are unrecognised in government policies, land management practices and economic markets due to their public goods characteristics, being both non-excludable and non-rivalrous (Costanza et al., 2014). However, the economic value of ecosystem service impacts can often be estimated indirectly through the use of non-market valuation techniques (Ranasinghe, 1994; Dixon et al., 2013; Harris and Roach, 2013). Valuing ecosystem services and their impacts using monetary information relies on a utilitarian (anthropocentric) interpretation of value, rather than a non-utilitarian perspective grounded in ethical, cultural and philosophical bases.

Environmental economists often link the services identified in their chosen classification framework for ecosystem services to the Total Economic Value framework. Total Economic Value refers to the aggregate economic value derived by individuals from a natural resource (Tietenberg, 1988; Hanley et al., 2013). The use of the Total Economic Value framework does, however, help to identify the most suitable non-market valuation techniques for valuing ecosystem service impacts.

When economists seek to estimate the economic value of ecosystem services given certain quantitative and/or qualitative changes, such as through the use of the contingent valuation method, rather than approximating total economic value, they are in fact estimating marginal changes in aggregate. This has been at the core of the work in national ecosystem service assessments and research, including the United Kingdom's National Ecosystem Assessment (Watson et al., 2011) and Norwegian studies aiming to incorporate ecosystem service unit values within cost-benefit analysis guidelines for the energy, environmental and transportation sectors (NOU, 2013).

1.4 The sustainable use of energy and Icelandic energy transition

1.4.1 Sustainable energy development

The links between energy use, sustainable energy development, environmental sustainability and the provisioning of ecosystem services are explicit. Sustainable energy development involves *“the provision of adequate energy services at affordable cost in a secure and environmentally benign manner, in conformity with social and economic development needs”* (IAEA/IEA, 2001). In much the same way that sustainable development represents a much wider concept than economic activity, sustainable energy development 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. By definition, a nation fulfilling the IAEA/IEA’s conceptualisation of sustainable energy development must also be focusing, at least in part, on the minimisation of environmental impacts and promotion of environmental sustainability. The avoidance of environmental harms is a pre-requisite of environmental sustainability, as the concept demands the avoidance of emissions of pollutants which exceed the waste assimilative capacities of the environment (Davíðsdóttir et al., 2007). Therefore, delivering energy projects with low or negligible environmental impacts is also an effective means of maintaining the provisioning of related ecosystem services at a given quantity and quality.

Energy systems transitioning from the use of fossil fuels to renewable sources of energy experience economic, environmental and social benefits and costs. The environmental benefits include reduced greenhouse gas emissions and improved public health and air quality. Less attention is commonly afforded to the environmental costs of harnessing renewable energy, perhaps in part because of a perception of their relative insignificance compared to those associated with fossil fuel alternatives. However, the expansion of renewable energy can entail land-use trade-offs and multiple environmental impacts which vary in degree, as well as temporal and spatial scale. Some of the most well-known impacts include the obstruction of landscape vistas by wind turbines, downstream ecosystem effects by hydropower, and the intensification of land-use and competition with food production through biofuels production (Hastik et al., 2015).

Geothermal power is also an example of a technology often considered to be environmentally benign, due to its lower greenhouse gas emissions compared to coal, oil or natural gas (Rybach, 2003). However, the utilisation of geothermal energy resources still results in environmental impacts, which may be temporary or irreversible depending on project specifics. These typically include landscape and visual effects (Shortall et al., 2015); emissions of toxic gases to the air and local watercourses (DiPippo, 1991; Goldstein et al., 2011); noise emissions (Bayer et al., 2013); emissions of solid waste (Heath, 2002); and land subsidence and seismicity (Rybach, 2003; Shibaki and Beck, 2003). Other impacts may occur in a project-specific setting, such as biodiversity loss associated with the displacement of forest lands or increased consumption of scarce sources of drinking water (Bayer et al., 2013; Shortall et al., 2015).

1.4.2 The Icelandic energy transition and likely future utilisation of geothermal fields

Over the past half a century, Iceland has experienced a comprehensive energy transition. For several centuries, abundant geothermal resources had been harnessed purely for washing and bathing. Until the early 1970s, the nation remained heavily reliant on imports of fossil fuels. As a small and remote nation, with a volatile currency, Iceland was particularly vulnerable to oil price shocks. Thus, for predominantly economic reasons, Iceland gradually shifted from the provision of space heating and hot water using fossil fuels – peat in earlier times, more commonly coal and oil in the 20th Century – to district forms of heating powered by geothermal energy (Björnsson, 2010). Today, Iceland can be considered something of a world leader in terms of the use of renewable energy, with 99.9% of electricity production and 86.5% of primary energy generation deriving from renewable energy sources (Orkustofnun, 2016).

Iceland is one of the most tectonically active locations on earth. In recent times, high-temperature geothermal fields have been harnessed for a multitude of applications, especially electricity production and direct uses such as space heating, district heating, industrial and agricultural processes, swimming pools and spas. The installed capacity of Iceland's geothermal power plants is currently 665 MW_e (Orkustofnun, 2016). Geothermal energy currently satisfies 96% of Iceland's total heat generation of 29 PJ (Orkustofnun, 2016). The majority of this generation is used for space heating (72.4%), with the remainder utilised in swimming pools (7.2%), snow melting (6.8%), fisheries (7.1%), industrial applications (3.6%), and greenhouses (2.4%) (Orkustofnun, 2016). In 2015, all bar 4 GWh of Iceland's total electricity generation of 18,798 GWh derived from renewable energy sources, with geothermal energy supplying 5,003 GWh

(26.6%) and hydropower nearly all of the rest. At the end of the 1970s, Iceland was home to three geothermal power plants with installed capacity of 140 MW_e. In the 37 years since, installed capacity has more than quadrupled to 665 MW_e (Orkustofnun, 2016). Mainly this growth has occurred in order to satisfy the electricity demands of energy-intensive industrial projects such as aluminium and ferrosilicon production.

Iceland is a world-leader in terms of renewable energy generation, it is subject to policies, as a member of the European Economic Area, which will necessitate increased supplies. Currently the nation is only around halfway towards satisfying the transport target set by Directive 2009/28/EC of the European Union, which requires Iceland to provide 10% of energy demand related to this sector from renewable energy sources by 2020. Furthermore, new energy-intensive industrial or information communication projects may emerge and the National Power Company, Landsvirkjun, also has ambitious plans to connect Iceland's electricity grid with Scotland's, via a submarine cable delivering 5 TWh of renewable electricity per annum. This level of generation is likely to require the development of new geothermal power plants and onshore wind energy resources (Landsvirkjun, 2016).

Given all of the possible needs, there is a very strong likelihood that at least some of Iceland's remaining high-temperature geothermal fields will be developed in the near future. The legislative basis determining license approvals, both for exploratory and productive activities, increases the likelihood that, if new energy resources are sought in Iceland, they will be derived from geothermal sources. Iceland's Master Plan for Nature Protection and Energy Utilisation provides a strategic framework for decision-making concerning energy projects. Enshrined in law since 2013, it is very similar to Strategic Environmental Assessment in terms of its land-use planning objectives, evaluating the suitability of potential geothermal and hydropower projects in Iceland. After a scoring and ranking process involving a broad range of environmental, economic and socio-cultural criteria, each energy project was classified as either 'suitable for development', 'under consideration' pending further information, or 'protected'. Under the 2013 version of the Master Plan, only 16 projects fall until the 'suitable for development' category. Of these, only 2 relate to hydropower, and the remaining 14 to high-temperature geothermal fields.

1.5 Use of non-market valuation techniques in decision-making

In a general international context, the use of non-market valuation techniques to inform policy and decision-making has only developed since the 1970s. Within the European Union, for example, the Treaty of Rome (1957) establishing the European Economic Community made no references to the environment. However, in 1973, the Community progressively introduced environmental legislation via Environmental Action Plans (Pearce and Seccombe-Hett, 2000). The fifth Environmental Action Plan, *Toward Sustainability*, made specific reference to economic valuation techniques, stressing that these were necessary to (a) take environmental impacts into account, and (b) develop meaningful cost-benefit methodologies in respect of actions impinging on the natural resource stock (European Commission, 1992).

In Iceland, although Environmental Impact Assessments have been required by law since the year 2000, the main criterion for determining the acceptability of proposed energy projects remains economic feasibility based on direct costs and benefits. Beyond the commercial advantages of not having to account for the economic costs of environmental impacts in cost-benefit analysis, a lack of expertise in carrying out non-market valuation techniques has potentially hindered the advancement of accounting practices that would satisfy the OECDs demands related to energy projects. Only a handful of non-market valuation studies have been undertaken so far – a hedonic pricing study on Mount Esja (Jóhanesson, 2003), five contingent valuation studies (Ásgrímsdóttir, 1998; Bothe, 2003; Kristofersson and Navrud, 2007; Lienhoop and MacMillan, 2007, Ragnarsdóttir, 2010), and an economic assessment of the ecosystem services related to Lakes Elliðavatn and Vífilsstaðavatn. Of these, only the contingent valuation study on Kárahnjúkar Hydropower Plant by Lienhoop and MacMillan (2008) related to an energy project prior to the commencement of production. No non-market valuation studies have yet occurred in Iceland in relation to forthcoming geothermal power projects.

1.6 Global history of non-market valuation studies connected to the preservation of geothermal areas

In a global sense, only one prior non-market valuation study has been conducted which sought to research preferences and willingness to pay for the preservation of geothermal areas, the contingent valuation study by Thayer (1981). The setting for Thayer's project was the Jemez Mountains in the Santa Fe National Forest, New Mexico. Noted for its variety of scenic attractions, varied flora, diverse geology and popularity as a site of recreational amenity, the study site also featured geothermal hot springs. Given that the wider region was already home to one of the few geothermal resources in the United States that had been developed at this time, Thayer was able to present a realistic survey scenario of a 100 MW electricity-generating geothermal power plant and erection of transmission lines in the Jemez Mountains. Although the concept of ecosystem services was in its infancy at this point and not directly referred to in his work, Thayer discussed the likely environmental impacts in terms of effects on stakeholder well-being, asserting that *“Recreation areas may have to yield to extractive activities as well as electric generation plants and transmission lines, all of which could have a negative impact on the outdoor recreation experience. Therefore, development of the geothermal reservoir could impose aesthetic damages upon the recreators of the region.”* (Thayer, 1981, p.37). Other environmental impacts included visual impacts from drilling activity, pipelines, transmission lines and construction of plant facilities; removal of vegetative cover and exposure of raw soil; emissions of noxious gases reducing local air quality; and increased noise levels compromising peace and opportunities for solitude (Thayer, 1981).

The irreconcilability of alternative land-uses was clearly delineated, with Thayer applying the contingent valuation method to estimate the economic benefits deriving from the preservation of the Jemez Mountains in their existing state. Using a bidding game format with randomly varied starting points to elicit willingness to pay an entrance fee for preservation of the area, and based on a sample of 106 campers and day-trippers, Thayer estimated mean WTP of US $2.60 (1977 prices). This would be equivalent to approximately US $10.25 if scaled up to 2017 prices. Although a useful means of establishing a potential entrance fee charge, Thayer’s study only surveyed recreational visitors to the Jemez Mountains, and thus it is not possible to use the mean statistic to estimate the Total Economic Value of preserving these resources intact. Given their renown, the population affected by a decision to develop a power plant in the Jemez Mountains was likely to be much broader than those surveyed. Non-use value, which may have been significant among individuals not frequenting the site or ever intending to do so, was only, at best, partially captured through Thayer’s focus on recreational visitors. Today, in the light of methodological advancements, it is more likely that Thayer would have adopted the travel cost method to estimate the consumer surplus associated with recreational amenity.

1.7 Summary of methods and results

This section provides a summary of the research questions, methods and results pertaining to each paper.

1.7.1 Paper I

Cook, D., Saviolidis, N. M., Davíðsdóttir, B., Jóhannsdóttir, L., & Ólafsson, S. (2017). Measuring countries' environmental sustainability performance – The development of a nation-specific indicator set. *Ecological Indicators*, *74*, 463-478.[2]

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Building on the work of Olafsson et al. (2014), the motivation for paper IV was to develop a methodology for selecting indicators of environmental sustainability, specific to the national context. In recognition of the tendency for existing environmental indices to focus on performance against generic policy targets and the promotion of ranking lists, this paper uses the case studies of Iceland and Norway to set out a robust process for selecting indicators of environmental sustainability, one that factors in stakeholder consultation. The focus of this paper was purely methodological and thus there was no attempt to provide a detailed evaluation or comparison of environmental sustainability performance between these two Nordic nations.

In this paper, the research questions were as follows:

1) How to determine a transparent and robust methodology for selecting indicators of environmental sustainability, specific to the national context?
2) What criteria should be applied to determine whether to select or reject potential indicators from a pool of options?
3) What data gaps currently prevent a comprehensive measurement of environmental sustainability in the cases of Iceland and Norway?

This paper outlines a five-stage methodology to the selection of indicators of environmental sustainability. This includes: (1) the use of initial focus group research (2) formation of an expert team to guide the selection

[2] The role of the doctoral student (David Cook) in this paper was to carry out all research activities relating to indicator selection, establishing valid sources of data and the methodology, and the writing of the paper. Nína Maria Saviolidis was responsible for data entry and developing graphs for the case studies of Iceland, and the other authors guided the doctoral student during the research activities and writing process.

process, (3) selection of an initial pool of pre-existing indicators, (4) establishment of criteria to guide the selection process, and (5) setting of appropriate policy or trend-based targets given the nation-specific context.

Focus group research was undertaken to ensure that stakeholders were both able to engage with and inform the process of indicator selection in consultation with experts. In so doing, the process of indicator selection was neither top-down nor bottom-up in character. Once the outcomes from these discussions were understood, the dominant themes were used to help guide the indicator selection process. Indicators were selected by the expert team from a pool of candidates based on four criteria: policy relevance, utility, soundness and data availability. Occasionally, the criterion of soundness was afforded greater weight in the selection process than data availability, so as to maintain the comprehensiveness of the indicator set.

A total of 23 indicators were selected from an initial pool of 30. Of these, 11 indicators related directly to issues connected to the environmental implications of energy use, including greenhouse gas emissions, renewable energy generation, and emissions of various air pollutants. The case studies of Iceland and Norway were used illustratively, identifying a graphical means of evaluating progress in future, more detailed analysis. The use of different evaluative techniques – radar charts for target-based indicators; traffic-lights for trend-based indicators – provided a straight-forward means of communicating national performance over time. In the case of the radar charts, it was easy to observe areas where new policy initiatives might be necessary to deliver compliance with targets for Iceland and Norway respectively.

The data gathering process revealed omissions connected to important criteria. These included the issues of biodiversity, soil erosion, fisheries and groundwater abstraction. A comprehensive temporal evaluation of national environmental sustainability performance in Iceland and Norway will require these data gaps to be filled. These gaps are also indicative of likely challenges facing other researchers who seek to apply the outlined indicator selection methodology to other national contexts.

1.7.2 Paper II

Cook, D., Davíðsdóttir, B., & Kristófersson, D. M. (2016). Energy projects in Iceland–Advancing the case for the use of economic valuation techniques to evaluate environmental impacts. *Energy Policy*, *94*, 104-113.[3]

Received: 1 December 2015 / Accepted: 29 March 2016 / Available online: 12 April 2016

The first paper seeks to explore in detail the potential for an inequality on decision-making to arise in connection to Icelandic energy projects. Although the environmental impacts of energy projects are published in Environmental Impact Assessments, a purely qualitative account of these is insufficient to ensure their sufficient arbitrage in decision-making. Evidence for this conclusion is drawn from theory connected to cost-benefit analyses, the legislative and policy framework particular to Iceland, and the case study of the Kárahnjúkar Hydropower Plant. This paper sets out the steps necessary to ensure the full welfare implications of developing Icelandic energy projects are accounted for and independently verified as part of the decision-making process.

The main research questions addressed by this paper are as follows:

1) What is the current decision-making basis with regards to Icelandic energy projects relating to accounting for environmental impacts?
2) What are the main changes needed to ensure that estimates of the economic value of environmental impacts relating to Icelandic energy projects are incorporated within decision-making processes? How might these processes be operationalised in practice?
3) What are the main non-market valuation techniques that could, in theory, be applied to estimate the economic value of ecosystem service impacts generated by Icelandic energy projects?

This paper provides a systematic review of Iceland's Master Plan for Nature Protection and Energy Utilisation. As a strategic guide for determining the general economic, environmental and socio-cultural suitability of renewable energy projects, for geothermal energy and hydropower, it meets its

[3] The role of the doctoral student (David Cook) in this paper was to carry out all of the research activities. Professors Brynhildur Davíðsdóttir and Daði Már Kristófersson guided the doctoral student during the research activities and writing process.

objectives. However, its influence is limited by design to an overarching role related to planning and programming. The scope of the Master Plan does not extend to identifying the specific environmental impacts of detailed project proposals, which necessitates the preparation of an Environmental Impact Assessment.

No energy project can be awarded a license by Orkustofnun, the National Energy Authority of Iceland, for exploratory or production work unless it falls within the Master Plan's 'suitable for development' category. Orkustofnun must also be satisfied that the proposed project satisfies an array of additional legislation, including the Environmental Impact Assessment Act. The administration of this Act is the responsibility of Skipulagsstofnun, the National Planning Agency, who issue a non-binding opinion on the 'acceptability' of the environmental impacts and proposed mitigation measures. In the case of the Kárahnjúkar Hydropower Plant, the various environmental impacts were determined to be 'unacceptable', but the opinion of Skipulagsstofnun was overridden by Orkustofnun following the intervention of Iceland's Minister of the Environment, Siv Friðleifsdóttir. This case leads to the observation of two regulatory weaknesses connected to the assessment of environmental impacts – first, in terms of authority, Skipulagsstofnun have insufficient power to reject energy projects when environmental impacts are deemed unacceptable, and second, the determination of 'acceptability' is a subjective affair, with the potential to become clouded by the vested interests of politicians and commercial interests.

Therefore, this paper advances the case for the use of non-market valuation techniques as part of a modernised Icelandic decision-making framework for awarding licenses. The incorporation of a legislative requirement for independently prepared cost-benefit analyses is essential to ensure the true welfare gains or losses of Icelandic energy projects are evaluated. This paper recommends that Skipulagsstofnun is granted responsibility for this role, particularly as the determination of compliance with the Environmental Impact Assessment Act already falls under their auspices. Standards for the preparation of cost-benefit analyses, incorporating the costs of environmental impacts, could be established along the lines of the approach in the United States connected to regulatory analysis, which are set out in detail within the publication 'Guidelines for Preparing Economic Analyses'. In addition, there needs to be a legislative stipulation ensuring that Orkustofnun must reject license applications for all energy projects failing the benefit-cost test.

Although the practice of carrying out non-market valuation techniques is in its infancy in Iceland, this paper discusses the various revealed and stated preference methods that could be applied to estimate the costs of the environmental impacts of energy projects. The methods set to be used in the contingent valuation studies on Eldvörp and Hverahlíð (see results in Paper III) are briefly summarised to provide examples of how the OECD's accounting requests could be met in practice for two geothermal fields.

1.7.3 Paper III

Cook, D., Davíðsdóttir, B., & Kristófersson, D. M. (2017). An ecosystem services perspective for classifying and valuing the environmental impacts of geothermal power projects. *Energy for Sustainable Development, 40*, 126-138.[4]

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This paper focuses directly on the application of an ecosystem services perspective to the environmental impacts deriving from the development of high-temperature geothermal fields. This perspective is selected as it provides an effective means of understanding linkages between impacts to the environmental and human well-being. Stakeholders are identified and impacts classified for the purposes of valuation, leading, potentially at least, to decision-makers possessing a better informed understanding of land-use trade-offs. Until this paper, the academic literature contained no studies which sought to identify, classify and value the ecosystem service impacts associated with developing geothermal power. Using a thematic rather than project-specific approach to the analysis in order to encompass the widest spectrum of likely ecosystem service impacts, this paper applied the CICES classification typology prior to determining whether the respective affects are best valued using monetary or non-monetary sources of information. A review is also conducted concerning of the suitability of the two information sources – Environmental Impact Assessments and Life Cycle Analysis – likely to be used by environmental economists when seeking to establish the degree of quantitative and qualitative change to the ecosystem services provisioned by geothermal areas.

The main research questions addressed by this paper are as follows:

[4] The role of the doctoral student (David Cook) in this paper was to carry out all of the research activities. Professors Brynhildur Davíðsdóttir and Daði Már Kristófersson guided the doctoral student during the research activities and writing process.

1) What are the main environmental and ecosystem service impacts likely to occur due to the development of high-temperature geothermal fields?
2) For each ecosystem service impact, should monetary or non-monetary information be used to estimate the value of change?
3) For cases where monetary information is deemed suitable, which of the non-market valuation techniques should be applied?
4) What are the best sources of information for environmental economists attempting to establish the degree of qualitative and qualitative change to ecosystem services affected by the development of high-temperature geothermal energy resources?

The main ecosystem service impacts affected by geothermal power projects are likely to include some or all of the following:

- Diminishment in the quantity of provisioned goods, such as genetic resources, freshwater and minerals.
- Diminishment in the quantity of regulating services, such as water purification, waste treatment and air quality regulation.
- Diminishment in the quantity and/or quality of various cultural services, including recreational amenity, spiritual enrichment, landscape aesthetics, inspiration, archaeological heritage, and non-use notions of value.

Although the academic literature includes an unsettled debate concerning whether monetary or non-monetary valuation techniques are appropriate for valuing ecosystem service impacts, this paper adopts a mixed approach. Three criteria – scientific validity, reliability and value commensurability – are applied to assess whether the value of the respective ecosystem service impacts should be estimated using monetary or non-monetary sources of information. This paper determines that non-monetary sources of information are most appropriate for impacts to cultural ecosystem services, those assimilative of philosophical notions of value, such as aesthetics or spiritual enrichment. Therefore, the scope of cost-benefit analysis should be limited to estimating the value of impacts to the sacrifice of provisioned goods, recreational amenity, and cultural associations related to non-use notions of economic value.

Although neither Environmental Impact Assessments nor Life Cycle Analysis is found to strictly embed an ecosystem services perspective into its process, the former is determined to be the more suitable method for determining the degree of quantitative and qualitative change in a geothermal energy context. Life Cycle Analyses for geothermal projects have, to date, lacked consideration of socio-cultural impacts, which may be the most significant effects in such a power project. Environmental Impact Assessments are close to fulfilling the needs of environmental economists, but some progress is still required to ensure that all stakeholders are consistently given sufficient voice and influence in its data-gathering processes.

1.7.4 Paper IV

Cook, D., Davíðsdóttir, B., & Kristófersson, D. M. (2018). Willingness to pay for the preservation of geothermal areas in Iceland – the contingent valuation studies of Eldvörp and Hverahlíð. *Renewable Energy*, *116*, 97-108.[5]

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The fourth paper is motivated by the OECD's call to commence accounting practices for the environmental impacts of energy projects in Iceland. Focused on two geothermal fields, Eldvörp and Hverahlíð, this paper details the results from contingent valuation studies concerning the economic value of their preservation. These study sites were chosen as they fall within the 'suitable for development' category set by Iceland's Master Plan for Nature Protection and Energy Utilisation, and both are considered likely to be development in the next few years for the purposes of electricity generation. The contingent valuation method was chosen to form an estimate of the total economic value of preserving these sites for two main reasons: (a) due to the perception of limited visitor numbers, ensuring that the travel cost method would have resulted in a considerable underestimate of total economic value, and (2) energy projects have been an issue of national concern in Iceland in recent years, leading to a likelihood that non-use value might represent a significant proportion of total economic value. In a global sense, these are the second and third contingent valuation studies seeking to estimate the economic value of preserving geothermal landscapes, occurring nearly four decades after the inaugural survey by Thayer (1981). They are also the first large-scale contingent valuation surveys on this subject, since

[5] The role of the doctoral student (David Cook) in this paper was to carry out all of the research activities. Professors Brynhildur Davíðsdóttir and Daði Már Kristófersson guided the doctoral student during the research activities and writing process. The doctoral student also collaborated with the University of Iceland's Social Science Research Institute during the survey design phase.

Thayer´s study was based on a sample size of only 106 recreational visitors to the Jemez Mountains in Santa Fe, New Mexico. Other than studies estimating willingness to pay for renewable electricity, there are no other known examples of non-market valuation studies in the context of geothermal energy.

This paper addresses the following research questions:

1) What is the mean and total economic value of preserving two of Iceland's high-temperature geothermal fields and how do these estimates compare?
2) What are the implications of these results for cost-benefit analysis practice in Iceland?

Survey participants were provided with impact scenarios derived from Environmental Impact Assessments for the two study sites. These were based on the development of a power plant at Hverahlíð and further exploratory research at Eldvörp. The contingent valuation studies elicited estimates of willingness to pay using interval regression and log-transformation. The surveys and scenarios therein were developed in conjunction with the University of Iceland's Social Science Research Institute. These were issued in April 2016 and the results analysed in the period June to August 2016. Both samples were found to be representative of the Icelandic population in terms of the full range of socio-demographic criteria.

Estimated mean willingness to pay was 8,433 ISK and 7,122 ISK for Eldvörp (n = 304) and Hverahlíð (n = 258) respectively. Scaled up to the Icelandic population, these amounts equated to total economic value of 2.11 and 1.78 billion ISK. The implications of these outcomes should be considered with some degree of caution due to the lack of prior academic knowledge concerning the preservation value of geothermal landscapes and ecosystems. However, they are approximate to 2% of the total construction costs of Hellisheiði, Iceland's largest existing geothermal power plant. These results are of sufficient scale to provide an evidence base in support of further research concerning the economic value of impacts to specific ecosystem services, such as recreational amenity. Furthermore, great emphasis can now be placed on calls for reform of the Icelandic decision-making framework for energy projects, as per paper I, bolstered by the knowledge that the economic value of preserving geothermal ecosystems is not insignificant.

1.7.5 Paper V

Cook, D., Eiríksdóttir, K., Davíðsdóttir, B., & Kristófersson, D. M. (2017). The contingent valuation study of Heiðmörk, Iceland – willingness to pay for its preservation. *Environmental Management, 209*, 126-138.[6]

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The fifth paper provides the first study on preferences and willingness to pay for the preservation of parkland landscapes in Iceland. The study is motivated by a desire to gain greater knowledge concerning the economic value of preserving a variety of landscape types in Iceland. The study site of Heiðmörk is a popular recreational area on the edge of Greater Reykjavík, which includes forests, lava fields, lakes, cycle and footpaths, rest areas and camping facilities. As such, the area provisions a wide range of ecosystem services to Icelanders, including recreational amenity, drinking water, carbon sequestration, electricity from a small hydropower plant, and habitat services for various fish and bird species. Although this paper reports the results from the contingent valuation study of the site – using broadly the same methodology as applied in the Eldvörp and Hverahlíð surveys – this is only one component of a comprehensive ecosystem services valuation project for the Heiðmörk site. Other non-market valuation techniques used (but not reported in this thesis) are the travel cost method, market pricing, and discrete choice experiments.

Due to the large sample size that could be secured in this study, this paper also included an experimental component. The sample were split into three sub-samples, each representative of the Icelandic population, and were asked their willingness to pay a lump-sum preservation tax for either one, five or ten years. The aim of this research was to look more deeply at a very lightly researched aspect of the contingent valuation literature – sensitivity of scope to payment vehicles.

[6] The role of the doctoral student (David Cook) in this paper was to carry out all of the background research, analysis and reporting activities. Kristín Eiríksdóttir prepared the contingent valuation survey, which was issued with the help of Capacent and use of their panel database. Professors Brynhildur Davíðsdóttir and Daði Már Kristófersson guided the doctoral student during the research activities and writing process.

This paper addresses the following research questions:

1) What is the mean and total economic value of preserving Heiðmörk?
2) How does willingness to pay vary given payment vehicles of varying duration?

The welfare estimates provided evidence that Icelanders consider Heiðmörk to possess considerable economic value, with taxpayers willing to pay a mean lump-sum tax in the range 17,039 to 24,790 ISK per payment to secure its preservation. This equates to estimated total economic value of between 5.87 and 35.47 billion ISK. The results were supportive of previous research, which has reported a ‘temporal embedding of payments’. Participants appeared unable to discriminate between payments vehicles of varying length.

2. Paper I: Measuring countries' environmental sustainability performance – the development of a nation-specific indicator set

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Measuring countries' environmental sustainability performance—The development of a nation-specific indicator set

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ABSTRACT

The complicated task of measuring environmental sustainability has often led to comparative evaluations of national performance using ranking lists and generic policy targets. In this paper, a set of national environmental indicators is determined through the deployment of a five-stage methodology, which includes the use of focus group research and formation of an expert team to guide the process, selection of an initial pool of pre-existing indicators, establishment of criteria to guide the selection process, and setting of appropriate policy or trend-based targets given the nation-specific context. The nations of Iceland and Norway are used as case studies to demonstrate an effective means of communicating indicator outcomes over time. National performance is first evaluated on an indicator-by-indicator basis and then summarised overall through a system of traffic lights and radar charts for trend and target-based indicators respectively. Via this analytical process, it also becomes clear that data shortages partially constrain the extent to which a nation's environmental sustainability performance can be deciphered. Improved data collection is necessary connected to the measurement of several environmental issues on a national scale, particularly the sustainability of fisheries, soil erosion and biodiversity.

1. Introduction

Measuring environmental sustainability and considering progress towards or away from related policy objectives is a complex operation. The comprehensive review by Olafsson et al. (2014) concluded that environmental sustainability indices, such as the EPI, EF and HPI, are currently only a starting point on the road to measuring a country's environmental sustainability performance. Use of expert judgment and incorporation of nation-specific analysis (including the setting of target standards) is always necessary to supplement the information contained within existing environmental indices, as this enables a holistic assessment to be formed (Moldan et al., 2012).

Improvements to the evaluation of environmental sustainability can be achieved through the creation of a set of indicators particular to similar nations or regions. Olafsson et al. (2014) discussed the formation of a set of environmental sustainability indicators suitable for nation-state analysis. Briefly, in the discussion section of their paper, the authors sketched out the framework for such an indicator set, bracketing indicators according to the six environmental sustainability themes of (1) energy performance; (2) waste management; (3) air quality and pollution; (4) water quality and pollution; (5) land use, agriculture and fisheries; and (6) biodiversity, forests and soil degradation.

Following on from the work of Olafsson et al. (2014), the aim of this paper is to communicate in detail an easily understood and transparent methodology for selecting indicators of environmental sustainability that can be applied to any country, leading, ultimately, to the formation of a comprehensive assessment of their environmental sustainability performance. This paper first reviews the usefulness of a pool of existing environmental sustainability indicators, considering their suitability with regards to the criteria of policy relevance, utility, soundness and data availability. Next, for each selected indicator and where recognised national or international target standards exist, these are determined for

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the two case study nations of Iceland and Norway.[1] These two Nordic nations are chosen for analysis due to their apparent environmental commonalities – both generate a very high proportion of electricity from renewable energy sources, while, at the same time, they are still transitioning towards an economy less reliant on fossil fuel consumption, particularly in the fisheries and transport sectors (Ingebritsen, 2012). However, the case studies will reveal considerable variations in environmental sustainability performance and provide an evidence base in support of the use of differentiated indicator targets to ensure each indicator is given a nation-specific rather than generic, regional context. In so doing, this paper's method will maintain the political relevance of the chosen indicator set, acting as a potential trigger for the instigation of improved policy initiatives for more environmentally sustainable outcomes in the future.

This paper is organised as follows. Section 2 begins by providing an overview concerning environmental sustainability and the role of indicators. Building on these initial understandings, Section 3 outlines the methodological approach and rationale for this paper's choice of certain indicators, target standards, and evaluative techniques. Section 4 details the available data and outcomes pertaining to the case studies of Iceland and Norway. The approach to the analysis in these case studies is succinct and largely illustrative of the practical application of the methodology, aiming to merely sketch out a brief commentary. In Section 5, the summary and discussion appraises the environmental sustainability performance of Iceland and Norway using two evaluative techniques: radar charts and a system of traffic-lights. Thereafter, the strengths and current practical limitations of the methodology are reflected upon.

2. Overview

2.1. Defining environmental sustainability

Often sustainable development has been interpreted as social and economic development that should also be environmentally sustainable (Brundtland Commission, 1987; Bina, 2013), but in recent years there has also been growing recognition that environmental sustainability has its own merits as a concept of importance (Goodland, 1995; WRI, 1995; OECD, 2001; Esty et al., 2005; Jordan and Lenschow, 2009; Dahl, 2012; Moldan et al., 2012). This paper adopts the widely cited definition of environmental sustainability espoused by Goodland (1995). Environmental sustainability is described as the endeavours society makes to "improve human welfare by protecting the sources of raw materials used for human needs and ensuring that the sinks for human wastes are not exceeded, in order to prevent harm to humans" (Goodland, 1995, p. 3).

2.2. Introduction to indicators of environmental sustainability

The publication of various environmental indicators at the national scale is nowadays widespread (Bell and Morse, 2008; Hák et al., 2012), and they are included within annually updated publications, such as those compiled by the European Environment Agency (EEA), International Energy Agency (IEA), OECD, and World Resources Institute (WRI). The examples of Canada, which uses environmental sustainability indicators to measure progress towards their Federal Sustainable Development Strategy (ECCC, 2013), and Ireland's Key Environmental Indicators (EPAI, 2012), typify the popularity of developing indicator sets dedicated to measuring the state of the environment on a nation-specific scale.

Formation by an expert team of a robust definition of environmental sustainability and clarification as to the interrelated processes, themes and environmental issues to be addressed

↓

Identification of a pool of indicators of environmental sustainability using focus group interviews and brainstorming exercises by experts, irrespective of data availability

↓

Establishment of criteria for selecting indicators

↓

Acceptance or rejection of indicators according to their degree of compliance with agreed criteria for selection

↓

Determination of appropriate targets for each accepted indicator

Fig. 1. Process of indicator selection.

Environmental indicators are attractive to policy-makers as they enable the formation of a transparent and easily understood way of comprehending the state of the environment (Heink and Kowarik, 2010; Dobbie and Dail, 2013). The academic literature communicates a range of arguments favouring the use of environmental indicators, including the monitoring of progress and portrayal of progress over time (Lehane et al., 1997; Olafsson et al., 2014) and provision of simplified data that clearly identifies national performance (Puig et al., 2014).

Indicators can play a central role in evaluating the effectiveness of policies implemented by measuring progress towards specific targets (DEFRA, 2003). They can also establish a basis for the setting of future policy objectives (DANTES, 2003) and communicate early-warning information concerning the changing state of the environment, indicating risk before serious harm has occurred (EPCEM, 2003). The use of environmental indicators can also increase public and political awareness of specific environmental issues (Gautam and Singh, 2010).

2.3. Selecting indicators of environmental sustainability

The selection of environmental indicators is a complex process due to their multifunctional and broad nature (Kurtz et al., 2001). Several methods exist for selecting such indicators, generally involving either a bottom-up or top-down approach. A bottom-up approach involves compiling the final set(s) of indicators after integrating the perceptions of various stakeholders, including the public (Chamaret et al., 2007). The top-down approach has certain advantages over bottom-up techniques as the insights of experts make it easier to directly link indicators to existing target standards (UNEP, 2006).

Puig et al. (2014, p. 125) argue for the use of "a rigorous validation process" when choosing indicators. This paper adopts a five-stage process to indicator selection which is closely akin to the US Environmental Protection Agency's recommended approach (EPA, 1996), commencing with the formation of a comprehensive definition of environmental sustainability, proceeding to accept or reject indicators from a large pool of options, before finally determining appropriate targets for accepted indicators. This process is summarised in the following flow diagram (Fig. 1) and described fully in Sections 2.3 and 2.4.

2.4. Importance of boundaries and target setting

The importance of boundaries or target thresholds to evaluate environmental performance has been the focus of the Planetary

[1] The spatial boundaries for the case studies are set by the jurisdictional boundaries of maritime states, as defined by the United Nations Convention on the Law of the Sea. Wherever data is available, the case studies analyse performance over the entire period of 1990–2011. In some cases the evaluation is less detailed due to a lack of data availability.

Boundaries project led by Johan Rockström of the Stockholm Resilience Centre. In the planetary boundaries work, critical values are used to define nine safe operating areas for humanity with respect to environmental systems and processes (Rockström et al., 2009). The goal for humanity is to stay within the safe operating space, an objective that has been communicated effectively through the use of radar charts to describe performance. Radar charts have also been used effectively in the Sustainable Society Index (Van de Kerk and Manuel, 2008) to identify the degree of compliance with various indicators of sustainable development.

3. Methodology

3.1. Indicator selection and rejection

Given the respective advantages of bottom-up or top-down approaches, this study adopted a two-stage approach, which involved focus group research (bottom-up) and indicator selection by a team of experts (top-down). First, focus group interviews were conducted with forty-two experts in six different issue areas in environmental sustainability, and these revealed the core issue areas to include in the assessment (Jóhannsdóttir et al., 2014; Olafsson et al., 2014). Second, expert judgement was applied to form a pool of potential indicators, chosen to represent the identified core issue areas. Indicators were chosen from a wide-range of existing sources (listed in Tables 1 and 2) and bracketed according to the six identified themes of environmental sustainability: energy performance; waste management; air quality and pollution; water quality and pollution; land use, agriculture and fisheries; and biodiversity, forests and soils (Olafsson et al., 2014).

The expert team – the authors, all of whom are academics and authors of a wide range of publications in the fields of environmental sustainability and climate change – selected indicators according to five criteria. These were as follows:

1) Policy relevance: could the indicator be closely related to an existing or future policy target?
2) Utility: did the indicator meet the needs of decision and policy-makers and the public in being easily understandable?
3) Soundness: did the indicator appear aligned with a consistent methodology for capturing the multiple components of environmental sustainability without presenting a risk of duplicating aspects?
4) Interpretability: was the indicator able to communicate meaningful[2] information concerning performance relative to environmentally sustainable outcomes?
5) Data availability and quality: was the indicator based on high quality[3] data with adequate coverage over time?

Criterions (3)–(5) were afforded the greatest weight, as this approach ensured the multiple dimensions of environmental sustainability were captured within the chosen indicator set. In the case of the sustainability of fisheries indicator, the expert team made a judgment call which led to its inclusion despite the absence of suitable data. This issue was deemed fundamental to environmental sustainability in a Nordic context, yet a suitable metric was not available. Occasionally proxy indicators were chosen by the expert team due to data shortages, such as the use of a municipal waste indicator to represent total waste generation. Their use ensured that the soundness of the indicator set was not overtly compromised, but at the cost of some utility and interpretability.

From an initial pool of 30 potential indicators, 23 were selected and 7 rejected for case study analysis. Tables 1 and 2 outline the selected and rejected indicators, including the reasons for their initial consideration and explanation of why they were subsequently selected or rejected by the expert team.

3.2. Setting of targets and trends

The use of environmental sustainability indicators has merit only when they are evaluated with respect to trends over time and, wherever practicable, meaningful targets. Moldan et al. (2012) contend that although the absolute value of the baseline for an indicator may not really matter, from an environmental sustainability perspective it is important to gauge and compare performance with an outcome that is deemed to be acceptable. Wherever recognised performance standards exist, the use of numeric target values can lend indicators meaning and distinguish them from what would otherwise constitute a set of raw data. In so doing, policy makers can be informed about the distance to target and potentially lead instigate new and improved policy initiatives.

In the first instance, the authors of this paper drew upon the work of the EEA in 1999, which set about forming and evaluating a core set of environmental indicators. Their approach was to evaluate indicators according to four questions of importance: (1) what is happening to the environment and humans; (2) does it matter; (3) are we improving; and (4) are we on the whole better off (EEA, 1999). Aspects (2) and (3) necessitate the evaluation of data over time and target standards via which to form performance comparisons. More recently, the EPI has adopted a distance-to-target approach for each of its indicators of environmental performance and, since 2010, has also calculated a trend-based index. The EPI's indicator targets are derived from international standards, for example, from environmental treaties or global organisations (such as the World Health Organization), scientific criteria, or, predominantly expert judgment (EPI, 2012).

This paper's approach broadly adhered to the EPI's approach to identifying appropriate targets, but two key distinctions were made. First, it was recognised that the EPI's targets are generic to all countries, a feature necessary for ultimate ranking lists to be formed, but this approach reduces the EPI's relevance in a national context – a very apparent aspect in the case study review of Iceland (Olafsson et al., 2014). Therefore, where national targets exist for certain indicators, these were preferred to undifferentiated international standards. Second, it was evident that for many indicators there do not exist any suitable international or national targets and expert judgment was insufficient to arrive at a meaningful target value. Rather, in these cases, trend-based analysis is a more appropriate form of appraisal (Moldan et al., 2012; Singh et al., 2012). This was particularly the case for indicators which seek to measure the intensities of activities, be these energy, emissions or GDP-related. For these indicators it is sufficient to understand that a reduction in intensity is attained. By reviewing the general direction of progress over time, a judgment can be formed concerning movement towards or away from environmentally sustainable outcomes.

Table 3 outlines the targets and sought-after trends for each of the selected indicators specific to the case studies of Iceland and Norway.

[2] The meaningfulness of the indicator data was evaluated according to relevance i.e. how closely it satisfied the needs of existing policy standards for related environmental issues. For example, the UNFCCC's greenhouse gas inventory provided the information necessary to determine a nation's emissions performance relative to the targets set by the Kyoto Protocol.

[3] We determined the quality of the data for each indicator based on its consistency, accessibility, completeness, and potential use in a policy setting. Data sources possessing a Quality Assurance Framework, such as those belonging to the Eurostat database, were preferred wherever practicable.

Table 1
Selected indicators of environmental sustainability.

Theme	Indicator	Measure	Data Sources	Justification and explanation
Energy performance	Carbon intensity of heat and electricity generation	Total GHG emissions (tCO_{2e}) per GWh_e of combined heat and electricity generation	IEA (2016a; 2016b); UNFCCC (2016b)	GHG emissions from fossil fuel combustion in heat and electricity generation can make a significant contribution to national greenhouse gas emissions. This indicator assesses the extent to which the fuel mix has affected the carbon intensity of heat and electricity generation.
	Energy intensity of economic activity	Total primary energy supply (ktoe) per unit of national GDP (converted to US $ using PPP at constant 2005 prices)	IEA (2016c; 2016d); OECD (2016); Statistics Iceland (2016); Statistics Norway (2016)	The energy intensity of economic activity provides a portrayal of the relative decoupling of energy use from GDP. Changes in the indicator can often reflect changes in the energy and fuel mix or the structure of national economies.
	Renewable energy generation	Percentage of renewable energy (including waste recovery) as a share of primary energy supply	IEA (2016c; 2016d; 2016e; 2016f)	There are many environmental impacts associated with the generation of energy from fossil fuels, including greenhouse gas emissions, resource depletion, emissions of air pollutants, ocean acidification, and water pollution.
Waste management	Total volume of municipal waste generation	Total generation of municipal waste (thousand tonnes)	Eurostat (2016)	Municipal waste is currently the best available proxy indicator for describing more general patterns in total waste generation across the Nordic nations. Data coverage for other wastes, including total and household waste, is sporadic.
	Recycling of municipal waste	Percentage of municipal waste that is recycled	Eurostat (2016)	Increased rates of recycling of municipal waste indicate more efficient waste management practices and potentially reduced future demand for natural resources.
	Waste sent to landfill	Percentage of municipal waste that is sent to landfill	Eurostat (2016)	Lower rates of sending waste to landfill are also indicative of more efficient waste management practices, placing less strain on natural resources.
Air quality and pollution	Total emissions of sulphur oxide (SOx)	Total measured in thousands of tonnes of SOx, only from man-made sources	OECD (2015a)	Emissions of sulphur oxide contribute to acid deposition, leading to potentially negative impacts on soil and water quality such as damage to crops, forests and other vegetation.
	Total emissions of nitrogen oxide (NOx)	Total measured in thousands of tonnes of NOx, only from man-made sources	OECD (2015a)	Emissions of nitrogen oxide contribute to eutrophication rates in water systems.
	Total emissions of PM 2.5	Total measured in thousands of tonnes of PM 2.5, only from man-made sources	OECD (2015a)	Fine particles in the form of particulate matter can have adverse effects on human health and be responsible for and/or contribute to a number of respiratory problems.
	Total emissions of PM 10	Total measured in thousands of tonnes of PM 10, only from man-made sources	OECD (2015a)	As per explanation for PM 2.5. Note that data for PM10 emissions is not currently reported by Iceland, therefore the current basis of analysis for this nation derives solely from PM 2.5.
	Total emissions of carbon monoxide (CO)	Total measured in thousands of tonnes of CO, only from man-made sources	OECD (2015a)	Carbon monoxide is an indirect greenhouse gas as it reacts with other atmospheric elements, leading to the formation of increased concentrations of methane and tropospheric ozone.
	Total emissions of non-methane volatile organic compounds (NMVOC)	Total measured in thousands of tonnes of NMVOC, only from man-made sources	OECD (2015a)	Emissions of NMVOC are linked to the formation of photochemical air pollution. This can lead to various negative impacts to human well-being, such as eye and throat irritation and respiratory problems.

Table 1 (*Continued*)

Theme	Indicator	Measure	Data Sources	Justification and explanation
	Total greenhouse gas emissions	Total measured in million tonnes of CO_2 equivalent ($MtCO_2e$) including and excluding land use, land use change and forestry (LULUCF)	UNFCCC (2016b)	Emissions of greenhouse gases, particularly anthropogenic carbon dioxide released through the combustion of fossil fuels, contribute to multiple global climate change impacts and exacerbate oceanic acidification.
	Carbon intensity of economic activity	Total GHG emissions (tCO_{2e}) per unit of national GDP (converted to US $ using PPP at constant 2005 prices)	Statistics Iceland (2016); Statistics Norway (2016); OECD (2016); UNFCCC (2016b)	This indicator provides an impression of the relative decoupling of greenhouse gas emissions from GDP. Changes in the indicator can often reflect changes in the energy and fuel mix or the structure of national economies.
Water quality and pollution	Fresh and groundwater abstraction	Percentages of fresh and groundwater abstraction as proportion of long term average available water	OECD (2015b)	Sporadic data available but reveals how water abstractions can place pressure on water resources.
	Wastewater treatment	Percentage of population connected to urban wastewater receiving at least secondary treatment	Eurostat (2016)	Wastewater from households and industry can have significant negative impacts on the quality of the water environment due to discharge of organic matter and toxic substances.
Land use, agriculture and fisheries	Pesticide use	Total pesticides applied to crops and seeds expressed in tonnes per thousand hectares of agricultural land	FAOSTAT (2016a)	The use of pesticides to reduce damage to crops and maintain yields can have damaging and toxic impacts on water quality, and terrestrial and aquatic biodiversity.
	Fertiliser consumption	Total fertiliser consumption (nitrogen and phosphates) expressed in tonnes per thousand hectares of agricultural land	FAOSTAT (2016b)	The use of fertilisers contributes to crop yields but nitrogen and phosphates contribute to soil acidification, water pollution, and losses of biodiversity.
	Sustainability of fish stocks	Average ratio of aggregated stock landings to abundance measured by scientific stock assessments	None available	The authors of this paper considered using the data for the Sea Around Us Project, which has been relied upon by the Environmental Performance Index. However, the use of indicators based on only catch data is potentially very misleading, leading to false conclusions concerning the sustainability of fish species in cases where the catch has declined due to reasons other than reduced abundance (Pauly et al., 2013). A satisfactory indicator could include a comparison of stock catches against stock abundance, the latter based on annual scientific stock assessments (Pauly et al., 2013). There is currently insufficient data available to form this indicator with any degree of reliability – for example, just five of Iceland's species and six of Norway's are currently subject to this procedure every year.
Biodiversity, forests and soils	Endangered species	Total number of threatened species on the red list	Ministry for the Environment and Natural Resources (2014); Norwegian Ministry for Climate and Environment (2014)	This indicator acts as a proxy for assessing progress towards existing policies on biodiversity by identifying the number of threatened mammals, birds, reptiles and plants. This indicator is not currently available in a time series format, merely the latest year available, which for most countries is the late 2000s. Irrespective of this, the methodology used to compile the red list from 2006 onwards differs from earlier versions, so comparisons over time cannot be formed.

Table 1 (*Continued*)

Theme	Indicator	Measure	Data Sources	Justification and explanation
	Forest increment and fellings	Fellings as percentage share of net natural increment	Eurostat (2015)	This indicator impresses the importance of achieving a balance between fellings and natural increment in order to ensure the long-term availability of timber and conditions for biodiversity, health, and recreation in forests. Viewed over time, annual fellings should not exceed the net annual increment. Currently this data is not collected for Iceland.
	Protection of areas	Total land and marine area of the International Union for the Conservation of Nature (IUCN) protected areas (km^2)	Protected Planet (2015)	Although not available in time series format, this indicator impresses the importance of securing the long-term conservation of natural areas due mainly to their biodiversity, cultural and recreational value.
	Soil erosion rates	Soil erosion by water and air (tonnes per hectare per year)	None available	Soil erosion leads to a decline in organic matter, nutrient content, and stored water, increasing the risk of flooding and landslides, while decreasing agricultural productivity and carbon sequestration capacities. Currently there is no data available to quantify this indicator, however, soil erosion is a known problem in Iceland and a considerable threat to the nation's environmental sustainability (Arnalds, 2001; Greipsson, 2012).

3.3. Summary evaluation

The case studies in Section 3 review Icelandic and Norwegian data patterns for each of the selected indicators. Following these, this paper's methodology distinguishes itself from existing assessments of national environmental sustainability – such as the OECD's periodic Environmental Performance Reviews – by utilising two different but complementary approaches to summarise overall national progress towards sought-after outcomes. Where quantification of targets was possible, a proximity-to-target approach is advanced to assess performance. Where indicators rely on trend-based data, a straight-forward traffic-lights system is set out to visualise performance changes over time.

The proximity-to-target appraisal of target-based indicators has been popularised in recent years by the EPI (Olafsson et al., 2014). Through a quantification of progress towards or away from recognised standards of environmental sustainability, there is the potential for the metric to highlight areas of concern and encourage governance institutions to instigate new policy initiatives for environmental betterment. The weakness of the EPI, which this paper's methodology strives to overcome, concerns its application of generic policy targets to all nations rather than reviewing outcomes in terms of a nation-specific context. Thus, the EPI's approach, in establishing a plurality of purpose, leads to direct performance comparison between all nations at the expense of meaningful insight.

Through the setting of national targets for environmental sustainability performance, clear boundaries are set with regards to the minimum acceptable outcome within a given timeframe. This is not say that the targeted performance is an ultimate objective, as targets reflect political feasibility and future convergence towards an 'environmental utopia' may be deemed preferable by policy-makers e.g. 100% of primary energy generation from renewable sources is evidently more sustainable than 90%. This paper indexes each target value to the number 100 and delineates (a) the area between 0 and 100 as an 'environmentally sustainable core green zone' at the centre of each radar chart, and (b) the area between 100 and 200 as 'an environmentally unsustainable red zone'. The proximity-to-target approach reflects the percentage via which indicator performance is over or away from the target e.g. a nation targeting the sourcing of 75% of their primary energy supply from renewable energy sources, but delivering only 62% would lie 17.33 points away from the environmentally sustainable boundary and thus have an index value in the environmentally unsustainable 'red zone' of 117.33. Equally, 'overachievement' of a target offers the potential for indicator performance to venture deep into the safe environmentally sustainable space towards the radar chart's core.

For trend-based indicators, there is no agreed boundary point indicating progress towards an environmentally sustainable outcome. There is, however, a reference point with which to compare improving or worsening performance. As Moldan et al. (2012) observe, even a vague reference point can be an important policy driver and stimulator of debate concerning the desirable environmental state to be attained. In this paper and wherever sufficient data is available, a rolling three-year average (starting wherever possible with the years 1990, 1991 and 1992) is used to determine trend-based progress towards or away from environmentally sustainable outcomes. The use of rolling averages encourages continual progress in line with sought-after trend directions, and also overcomes some of the vagaries associated with one-off irregularities in performance. With regards to the analysis of trend-based indicators, this paper applies the approach taken within the UK's Sustainable Development Indicators, whereby a set of traffic lights were used to communicate 'rule of thumb' progress (DEFRA, 2003). The traffic lights are as follows:

GREEN = improving
YELLOW = little or no change
RED = deteriorating
GREY = no data available for a given year

Table 2
Rejected indicators of environmental sustainability.

Theme	Indicator	Measure	Potential Data Sources	Justification and explanation
Energy performance	Transmission losses from electricity generation	Percentage of electricity generation resulting in transmission losses	International Energy Agency for electricity generation and transmission loss data	In the case of the Nordic countries, transmission losses are a) very low, b) consistent and predictable, and c) generally replaced by renewable energy generation.
	Generation of heat and electricity from renewable energy sources	Percentage of aggregated generation from renewable energy sources	International Energy Agency for heat and electricity generation	Data is available but the indicator duplicates the aspects contained within the selected indicator of 'renewable energy generation'.
Waste management	Total volume of waste generated	Total volume of waste generation in thousand tonnes	Eurostat databases	Available data is very limited for total waste generation, especially in the case of Iceland. Therefore, given comprehensive data availability across the Nordic region, the proxy indicator of 'total volume of municipal waste generation' has been selected instead.
	Total volume of hazardous waste generated	Total volume of hazardous waste in thousand tonnes	Eurostat databases	Available data is very limited for total hazardous waste generation as it falls within the reporting compass of total waste generation.
Water quality and pollution	Biochemical oxygen demand (BOD) in rivers	Milligrams of oxygen per litre at 20 °C (mgO_2/L)	None currently available for Iceland and Norway	Where the BOD is high, it can indicate potentially dangerous implications for a river's biodiversity, as it suggests that levels of dissolved oxygen are falling. As there is currently no data available for this indicator in Iceland or Norway, a satisfactory proxy indicator is fertiliser use in the land use, agriculture and fisheries theme.
Land use, agriculture and fisheries	Area of organic farming	Percentage of total utilised agricultural area occupied by organic farming	Eurostat databases	Although organic farming places great emphasis on themes of environmental protectionism, data availability for this indicator is very inconsistent across the Nordic region.
	Built up areas	Percentage of built up land area as a share of total land area	Eurostat databases	The percentage of built up areas in itself was not deemed to be an indicator of environmental sustainability due to difficulty in interpreting its environmental sustainability implications in a national context, but associated environmental impacts of increased urbanisation were, which were captured in other indicators.

Where an indicator has changed by less than 1 percentage point from one three-year average to the next, it is considered to relate to the yellow traffic light. In cases of missing data, the three-year rolling average relates to the last three years on which data was available – for instance, if for the year 2010 an indicator was missing data from 2008 and 2009, then the three-year rolling average would be comprised of data entries from 2006, 2007 and 2010.

For the purposes of the analysis in this paper, which is illustrative of a new methodology rather than an examination of underlying causal factors, the year 2011 is chosen to display radar graphs for the target-based indicators pertaining to the two case studies. For trend-based indicators, the traffic lights outcomes from the years 2007–2011 are analysed. Thus the three-year rolling average reference points for 2007 encompass the data entries for years 2005, 2006 and 2007 wherever these are available, or earlier points if not.

4. Case study analysis

This section of the paper describes the performance of Iceland and Norway according to each of the selected indicators wherever data is available, and briefly reviews performance with respect to either the target or sought-after trend. In terms of the analytical approach, where indicators are trend-based and progress is quantified using identical units (for example, in the case of the carbon intensity of electricity generation indicator), Iceland and Norway's performance is analysed using a single graph to ensure ease of comparison. Where indicators are target-based, Icelandic and Nor-

Table 3
Targets or sought-after trends in performance: Iceland and Norway.

Theme	Indicator	Iceland	Norway
Energy performance	Carbon intensity of heat and electricity generation	Trend-based decrease	Trend-based decrease
	Energy intensity of economic activity	Trend-based decrease	Trend-based decrease
	Renewable energy generation	Iceland's National Renewable Energy Action Plan requires the share of renewable energy in the primary energy supply needs to be 72% by 2020 to satisfy the requirements of EU Directive 2009/28/EC.	Norway's National Renewable Energy Action Plan requires the share of renewable energy in the primary energy supply needs to be 67.5% by 2020 to satisfy the requirements of EU Directive 2009/28/EC.
Waste management	Total volume of municipal waste generation	Trend-based decrease	Trend-based decrease
	Recycling of municipal waste	50% recycling rate as per the EU's Waste Framework Directive (2008/98/EC)	50% recycling rate as per the EU's Waste Framework Directive (2008/98/EC)
	Waste sent to landfill	Trend-based decrease	Trend-based decrease
Air quality and pollution	Total emissions of sulphur oxide (SO_x)	Trend-based decrease	Norway's emissions ceiling for 2010 under the Gothenburg Protocol is 22 Gg; for 2020 it is also 22 Gg
	Total emissions of nitrogen oxide (NO)	Trend-based decrease	Norway emissions ceiling for 2010 under the Gothenburg Protocol is 156 Gg; for 2020 it is also 156 Gg
	Total emissions of particulate matter (PM) 2.5	Trend-based decrease	No 2010 target is set by the Gothenburg Protocol so a trend-based decrease applies, but for 2020 the figure is 28 Gg
	Total emissions of PM 10	Trend-based decrease	Trend-based decrease
	Total emissions of carbon monoxide (CO)	Trend-based decrease	Trend-based decrease
	Total emissions of non-methane volatile organic compounds (NMVOCs)	Trend-based decrease	Norway's emissions ceiling for 2010 under the Gothenburg Protocol is 195 Gg; for 2020 it is 132 Gg
	Total greenhouse gas emissions	Kyoto Protocol target for first commitment period 2008–2012 – Iceland is allowed to increase GHG emissions by 10% compared to base year of 1990, plus an exceptional allowance of 1600 t per year on average for certain heavy industry project under Decision 14/CP.7	Kyoto Protocol target for first commitment period 2008–2012 – Norway is allowed to increase GHG emissions by 1% compared to the base year of 1990
	Carbon intensity of economic activity	Trend-based decrease	Trend-based decrease
Water quality and pollution	Fresh and groundwater abstraction	Trend-based decrease	Trend-based decrease
	Wastewater treatment	Trend-based increase	Trend-based increase
Land use, agriculture and fisheries	Pesticide use	Trend-based decrease	Trend-based decrease
	Fertiliser consumption	Trend-based decrease	Trend-based decrease
	Sustainability of fish stocks	Insufficient data to currently determine, but could perhaps be linked in the future to Strategic Goal B, Target 6 of the Aichi Biodiversity Targets – by 2020, all fish and invertebrate stocks and aquatic plants are managed and harvested sustainably	Insufficient data to currently determine, but could perhaps be linked in the future to Strategic Goal B, Target 6 of the Aichi Biodiversity Targets – by 2020, all fish and invertebrate stocks and aquatic plants are managed and harvested sustainably
Biodiversity, forests and soil degradation	Endangered species	Trend-based decrease based on Aichi Strategic Objective C, Target 12 – by 2020 the extinction of known threatened species has been prevented and their conservation status, particularly of those most in decline, has been improved and sustained.	Trend-based decrease based on Aichi Strategic Objective C, Target 12 – by 2020 the extinction of known threatened species has been prevented and their conservation status, particularly of those most in decline, has been improved and sustained.
	Forest increment and fellings	Trend based decrease in ratio of fellings to increment	Trend based decrease in ratio of fellings to increment
	Protection of areas	Aichi Strategic Goal C, Target 11 – by 2020, at least 17 per cent of terrestrial and inland water, and 10 per cent of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved.	Aichi Strategic Goal C, Target 11 – by 2020, at least 17 per cent of terrestrial and inland water, and 10 per cent of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved.
	Soil erosion rates	Trend-based decrease as advised by the EU Thematic Strategy on the Sustainable Use of Natural Resources	Trend-based decrease as advised by the EU Thematic Strategy on the Sustainable Use of Natural Resources

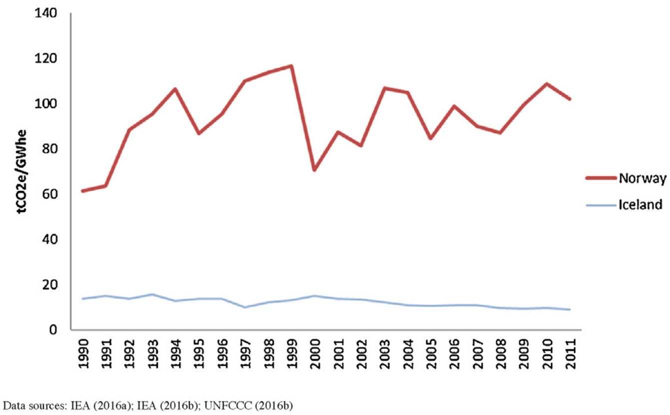


Fig. 2. Iceland and Norway – carbon intensity of heat and electricity generation (1990–2011).

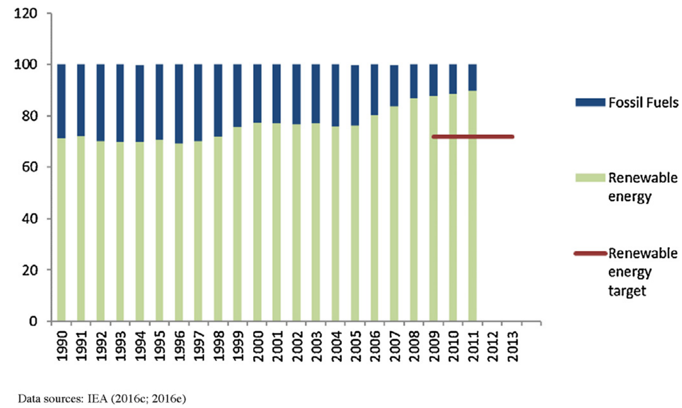


Fig. 4. Iceland – percentage share of renewable energy in primary energy supply (1990–2011).

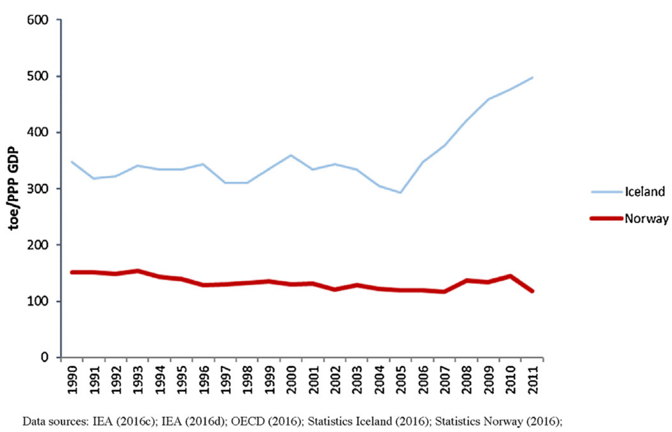


Fig. 3. Iceland and Norway – energy intensity of economic activity (1990–2011). (Note: GDP in US $, 2005 prices, converted using PPP)

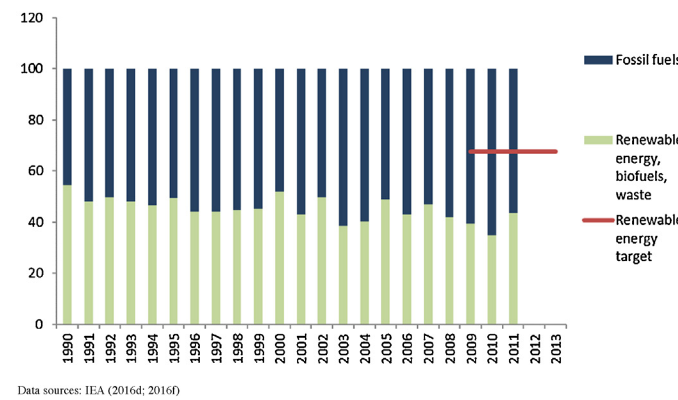


Fig. 5. Norway – percentage share of renewable energy in primary energy supply (1990–2011).

wegian performance is displayed using separate charts, except in cases such as the protected areas indicator, where the respective targets are identical.

4.1. Energy performance

Iceland's carbon intensity of heat and electricity production is very low in an international context. Peaking at 15.59 tCO_2/GWh_e in 1993, by 2011 the statistic had reduced to a low of 9.05 tCO_2/GWh_e (see Fig. 2). The nation sources nearly 100% of its heat and electricity production from renewable energy sources and has largely decarbonised energy production on a nationwide scale. Norway's carbon intensity of heat and electricity generation is much higher and prone to greater fluctuations than Iceland, peaking at 116.66 tCO_2/GWh_e in 1999. Although Norway has, like Iceland, largely decoupled greenhouse gas emissions and electricity production, the nation's carbon intensity of heat and electricity production was influenced by increased demand for heat from fossil fuel sources.

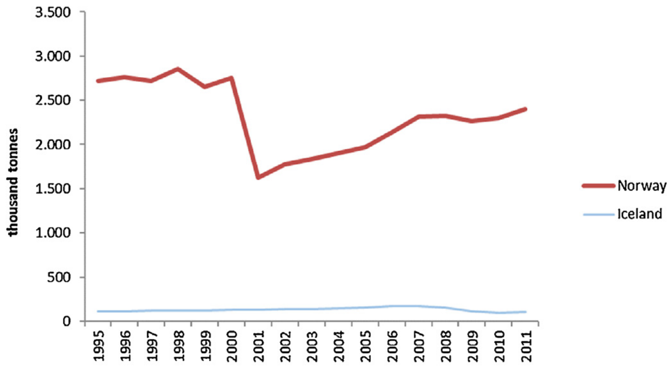
In the case of Iceland, the energy intensity of economic activity was broadly unchanged in the period 1990–2004, but increased by nearly 70% after 2005 (see Fig. 3). The majority of this increase can be explained by growth in the primary energy supply. In contrast, Norway's energy intensity of economic activity was largely unchanged over the period 1990–2011, with increases in the primary energy supply generally being matched by growth in GDP.

As Fig. 4 displays, Iceland has increased its share of renewable energy in the primary energy supply in the period 1990–2011. The majority of this expansion has occurred in the period 2005–2011, during which time the share of renewable energy output has increased from 76.37% to 89.75%. Current national performance thus far exceeds the 72% target set by Iceland's National Renewable Energy Action Plan to satisfy the requirements of EU Directive 2009/28/EC.

Norway has not made progress towards satisfying their National Renewable Energy Action Plan target, which requires 67.50% of the primary energy supply in the year 2020 to be provided by sources of renewable energy. Despite increases in the production of energy from biofuels and waste, Fig. 5 reveals that the share of renewable energy in Norway's primary energy supply was 51.08% in 1990, and lower than this percentage every year thereafter.

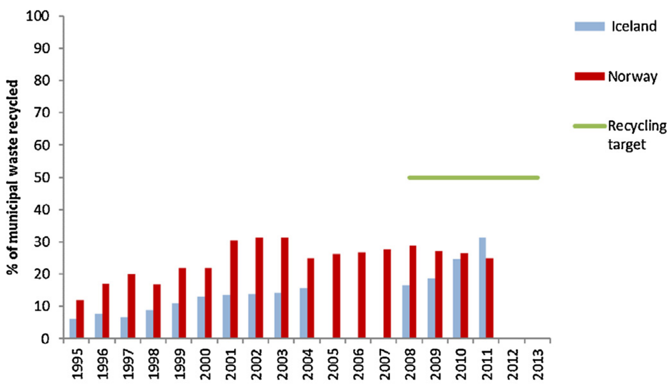
4.2. Waste management

Viewed over the period of data availability, 1995–2011, Iceland's performance in terms of municipal waste generation can be considered across two periods (see Fig. 6). From 1995–2007, the nation's total volume of municipal waste increased from 114 to 174 thousand tonnes. Thereafter, year-on-year reductions occurred, and in 2011 the total volume had fallen to 102 thousand tonnes. Norway's data must also be evaluated according to two distinct periods, but for methodological reasons. Over the period 1995–2000, Norway increased its volume of generation by 1.21%. However, from 2001 onwards, the Norwegian data excludes industrial waste handled by municipal authorities, and this largely explains the reduction of 1126 thousand tonnes between 2000 and 2001. From 2001 to 2011, volumes increased nearly every year, and were enlarged by 47.51% over this period.



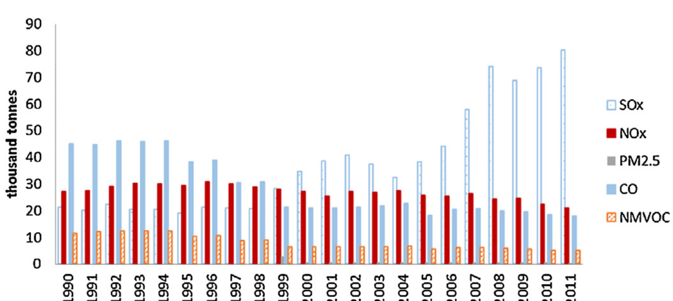
Data source: Eurostat (2016)

Fig. 6. Iceland and Norway – total volume of municipal waste generation (1995–2011).



Data source: Eurostat (2016)

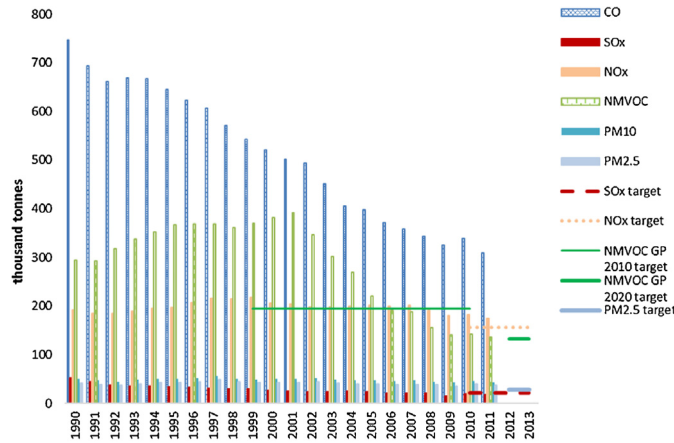
Fig. 7. Iceland and Norway – recycling rates for municipal waste (1995–2011). (Note: no data for Iceland 2005–2007)



Data source: OECD (2015a)

Fig. 8. Iceland – total quantity of emissions: SOx, NO_x, PM 2.5, CO and NMVOC (1990–2011).

In recent years, Iceland has increased the proportion of waste that is recycled and decreased its share sent to landfill sites. As Fig. 7 identifies, the material recycling rate has increased from a low of 6.14% in 1995 to a peak of 31.37% in 2011. However, this performance remains 18.63% short of the 50% recycling rate target set by per the EU's Waste Framework Directive (2008/98/EC). Norway has had success in doubling its volume of material recycling but, as a proportion of total municipal waste, performance has reduced from a peak of 31.46% in 2002 to 24.89% in 2011. This was the nation's lowest recycling rate since 2000 and 25.11% shy of the EU's 50% target.



Data source: OECD (2015a)

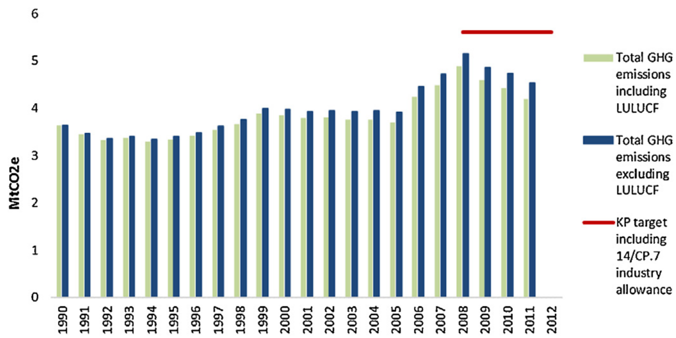
Fig. 9. Norway – total quantity of emissions: CO, SOx, NO_X, NMVOC, PM10 and PM2.5 (1990–2011).

4.3. *Air quality and pollution*

Fig. 8 sets out Iceland's total quantity of various pollutant gases during the period 1990–2011. The biggest growth in emissions relates to SOx, which have increased from 21.23 to 80.18 thousand tonnes over the period 1990–2011. Emissions of PM 2.5 have been especially variable, peaking at 3.00 thousand tonnes in 1999 and falling to a low of 0.26 thousand tonnes in 2011, with reports of 0.50-0.69 thousand tonnes in the years in between. Although increasing in the period 1990–1993, the nation's CO emissions have been on a downward trend in the years thereafter, reducing from 46.23 to 17.89 thousand tonnes between 1994 and 2011. Emissions of NOx and NMVOC have also fallen in recent years. In the case of the former, these peaked at 30.68 thousand tonnes in 1996, but had reduced to a low of 20.89 thousand tonnes in 2011. Emissions of NMVOC were highest in 1994 at 12.40 thousand tonnes, but in 2011 they had reduced by 58% from this level.

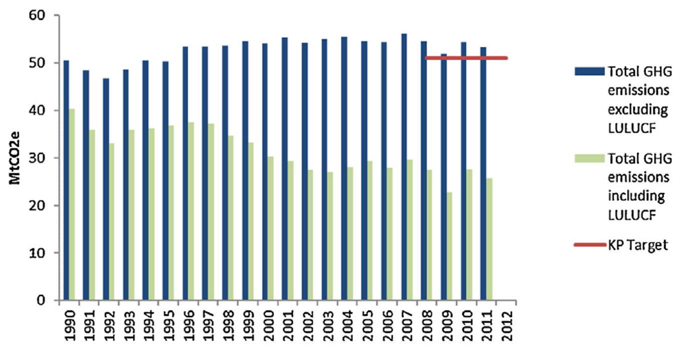
Fig. 9 sets out Norway's total quantity of various pollutant gases during the period 1990–2011. Since 1990, Norway has made almost year-on-year progress in reducing its quantity of SOx emissions and complied with the Gothenburg Protocol's ceiling of 22 thousand tonnes for the year 2010. Norwegian efforts to reduce NOx emissions have taken longer to come to fruition, but from 1999 to 2011 these have reduced from 217.20 to 174.23 thousand tonnes. These remain above the Gothenburg Protocol's emission ceiling of 156 thousand tonnes for the year 2010. Norwegian emissions of PM 2.5 reduced by 11.66% between 1990 and 2011. CO emissions in Norway have declined significantly from 747.23 to 309.42 thousand tonnes in the period 1990–2011. Emissions of NMVOC in Norway have fallen by two-thirds from a peak of 391.69 thousand tonnes in 2001–135.94 thousand tonnes in 2011. Compliance has been attained with regards to the Gothenburg Protocol's target for emissions of NMVOC to not exceed 195 thousand tonnes in 2010. Furthermore, Norway remains on track to meet the Gothenburg Protocol's second emissions ceiling target for NMVOC of 132 thousand tonnes by 2020.

Fig. 10 sets out Iceland's greenhouse gas emissions over the period 1990–2011. The Kyoto Protocol's target for Iceland is to increase annual emissions by no more than 10% compared to a 1990 baseline in the first-phase period of 2008–2012. In the first-phase and in accordance with Decision 14/CP.7, Iceland was also allowed to report separately an average of 1.6 thousand tonnes per year from certain industrial projects. This was given the proviso that the projects were (a) responsible for more than 5% of the total greenhouse gas emissions of Iceland in 1990, and (b) fuelled



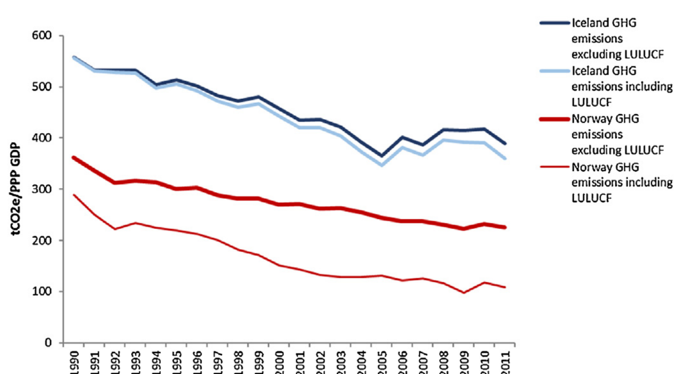
Data source: UNFCCC (2016b)

Fig. 10. Iceland – total greenhouse gas emissions (1990–2011).



Data source: UNFCCC (2016b)

Fig. 11. Norway – total greenhouse gas emissions (1990–2011).



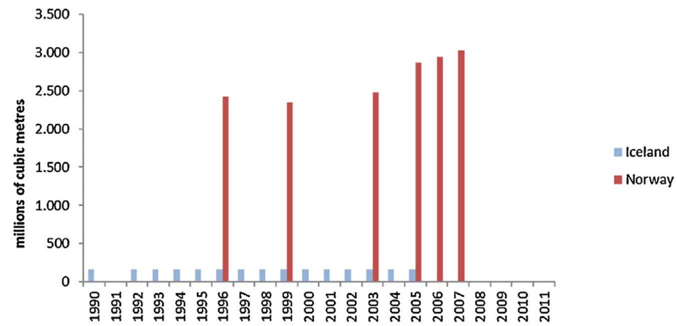
Data sources: Statistics Iceland (2016); Statistics Norway (2016); OECD (2016); UNFCCC (2016b)

Fig. 12. Iceland and Norway – Carbon intensity of economic activity, including and excluding LULUCF (1990–2011).
(Note: GDP in US $, 2005 prices, converted using PPP)

by renewable energy. In order to comply with the Kyoto Protocol, Iceland's emissions must not exceed 5.60 $MtCO_2e$, and Iceland has met this standard for the first-phase (UNFCCC, 2016a). In 2011, emissions, after accounting for LULUCF and those amounts satisfying Decision 14/CP.7, were 4.19 $MtCO_2e$, a 25.18% betterment of the Kyoto Protocol target.

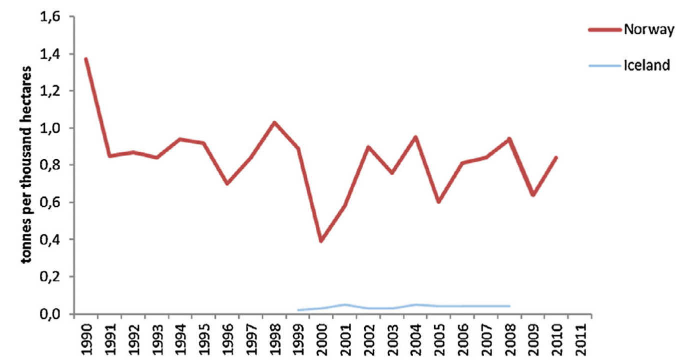
As Fig. 11 illustrates, including LULUCF, Norway's greenhouse gas emissions have reduced from 40.32 $MtCO_2e$ to 25.71 $MtCO_2e$ over the period 1990–2011, a fall of 36.24%. The nation is thus compliant with the Kyoto Protocol target for the first phase, which allowed a 1% increase.

The carbon intensity of Iceland's economic activity mirrors the preceding trends relating to the carbon intensity of heat and electricity production (see Fig. 12). In 1990, this indicator (excluding LULUCF) was at a peak of 556.25 tCO_2e/GDP, but by 2011 had



Data source: OECD (2015b)

Fig. 13. Iceland and Norway – gross water abstraction (1990–2007).
(Note: no data for Iceland in 1991, 2006 and 2007; no data for Norway in 1990–1995, 1997, 1998, 2000–2002 and 2004)



Data sources: FAOSTAT (2016a)

Fig. 14. Iceland and Norway – national pesticide use (1990–2010).
(Note: no data for Iceland 1990–1998 and 2009–2010)

reduced by 35.22% to 360.32 tCO_2e/GDP. Having reached a low of 346.45 tCO_2e/GDP in 2005, there was an increase in the period 2008–2010 in response to the economic recession, however, the more general downward trend relates to an expansion in industrial activities fuelled by renewable energy. Norway's carbon intensity of economic activity (excluding LULUCF) exhibited a very similar trend to Iceland's, falling by 37.56% from 361.30 to 225.58 tCO_2e/GDP over the period 1990–2011.

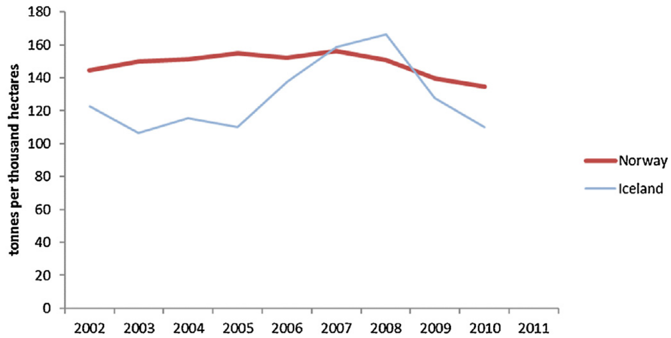
4.4. Water quality and pollution

In the limited period where data is available, Iceland's abstraction of water resources declined from 167 million cubic metres to 165 cubic metres (see Fig. 13). Similarly, very limited data is available on Norway's gross water abstraction. In the period 2003–2007, gross water abstraction increased from 2476 million cubic metres to 3026 million cubic metres, an uplift of 22.21%.

In recent years, the practice of at least secondary wastewater treatment has commenced in Iceland, but by 2005–the last year of available data – only 2% of the population was connected to this service, and mainly this was due to the very low population density in Iceland and effective waste dilution capacity of the ocean. Between 1990 and 2011, the share of the Norwegian population connected to urban wastewater treatment offering at least secondary treatment has increased from 44% to 61% (Eurostat, 2016).

4.5. Land use, agriculture and fisheries

Fig. 14 identifies Iceland and Norway's pesticide use for the years where data was available. Usage has varied in Iceland from an initial low-point 0.05 tonnes per thousand hectares to peaks in 2001 and 2004 of 0.05 tonnes per thousand hectares. However, these values



Data sources: FAOSTAT (2016b)

Fig. 15. Iceland and Norway – national fertiliser use including all nitrogen and .

are all very low in a European context, and increases in pesticide use since 1999 relate mainly to small scale expansion in Icelandic crop production (OECD, 2014). In Norway, there is data available for the period 1990–2010, and Fig. 14 reveals considerable fluctuations in amounts used, with no particular trend apparent.

Data on fertiliser use for Iceland and Norway were available for the period 2002–2010 (see Fig. 15). In the case of Iceland, little variance is apparent in phosphates consumption and changes to the total are caused almost entirely by differences in nitrogen usage, which were at their highest in 2008 at 122.57 tonnes per thousand hectares, representing 73.73% of total consumption. Norwegian fertiliser use has also been highly variable but shown gradual decline since 2007. Unlike Iceland, reductions in the consumption of nitrogen have sometimes been offset by increases in the use of phosphates, such as in the year 2010.

4.6. Biodiversity, forests and soil degradation

Based on the fourth National Report submitted by Iceland as part of their requirements under the Convention on Biological Diversity, there are a total of 267 species on the threatened red list. These include the following species: 74 mosses (27.72%), 67 lichens (25.09%), 52 vascular plants (19.48%), 42 algae (15.73%), and 32 birds (11.99%) (Ministry for the Environment and Natural Resources, 2014). According to the fifth National Report submitted by Norway in 2014, there are a total of 2398 species on the threatened red list. These are dominated by 784 species (32.69%) of invertebrates, 418 (17.43%) fungi, 220 (9.17%) vascular plants, and 216 (9.01%) lichens (Norwegian Ministry of Climate and Environment, 2014). With regards to the 16 threatened mammal species, these include the brown bear, lynx, wolf and wolverine (OECD, 2011).

In terms of the sustainable use of forest resources, Iceland has yet to file any data but there have been four years when Norway has reported fellings as a share of net annual increment: 1990, 2000, 2005, and 2010. For the three most recent data entries, this figure has been in the band 48.39–50.30% (Eurostat, 2015).

The total size of protected land areas in Iceland is currently 17,063 km^2, which equates to 17% of the national land area (Fig. 16). Thus performance is matching the Aichi Target for at least 17% of national terrestrial areas and inland waters to be protected by 2020. The total size of protected areas in Norway has most recently been estimated as 55,442 km^2, also equal to 17% of national land area and compliant with the same Aichi Target.

As Fig. 16 also identifies, a further 2768 km^2 (0.37%) of Iceland's marine area is designated as protected. However, this performance currently falls short of the Aichi Target for 10% of marine areas to be protected by 2020. A further 5285 km^2 (0.31%) of Norway's marine area is designated as protected, and therefore the nation is similarly adrift of the same Aichi Target.

5. Summary evaluation and discussion

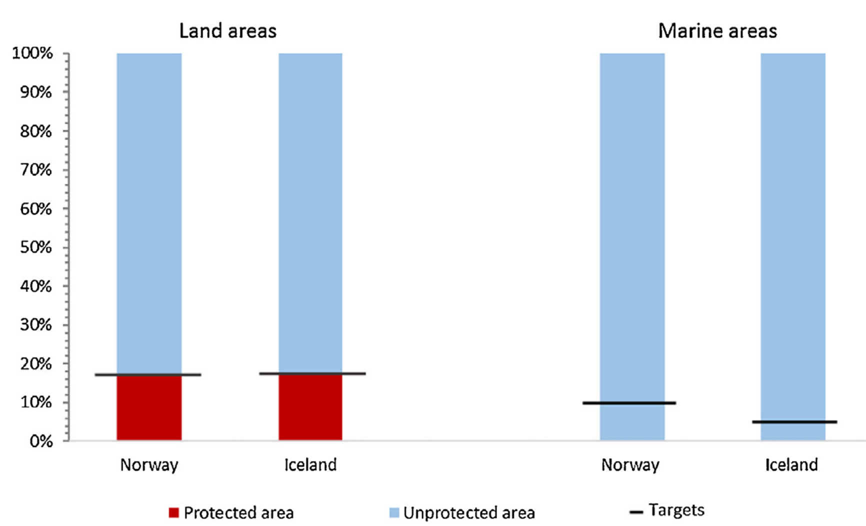
5.1. Summary evaluation

5.1.1. Target-based indicators – radar charts for 2011

The performances of Iceland and Norway in 2011 are summarised in Figs. 17 and 18 respectively. Iceland is meeting three of its five targets connected to the reduction of greenhouse gas emissions, renewable energy generation and protected land areas. Both countries remain a considerable distance away from compliance with targets for the recycling of municipal waste and protection of marine areas. In the case of Norway, three out of nine targets are met, with the successes relating to the reduction of greenhouse gas emissions, sulphur oxide emissions, and protected land areas.

5.1.2. Trend-based indicators – traffic lights evaluation for years 2007–2011

The performances of Iceland and Norway with respect to the various trend-based indicators for the period 2007–2011 are set out



Data sources: Protected Planet (2015)

Fig. 16. Iceland and Norway – percentage of protected land and marine areas (2015).

Table 4
Trend-based environmental sustainability performance of Iceland, 2007–2011. (For interpretation of the references to color in this table, the reader is referred to the web version of this article.)

Theme	Indicator	2007	2008	2009	2010	2011
Energy performance	Carbon intensity of heat and electricity generation					
	Energy intensity of economic activity					
Waste management	Total volume of municipal waste generation					
	Waste sent to landfill					
Air quality and pollution	Total emissions of sulphur oxide (SOx)					
	Total emissions of nitrogen oxide (NOx)					
	Total emissions of PM 2.5					
	Total emissions of PM 10					
	Total emissions of carbon monoxide (CO)					
	Total emissions of non-methane volatile organic compounds (NMVOC)					
	Carbon intensity of economic activity					
Water quality and pollution	Fresh and groundwater abstraction					
	Wastewater treatment					
Land use, agriculture and fisheries	Pesticide use					
	Fertiliser consumption					
	Sustainability of fish stocks					
Biodiversity, forests and soil degradation	Endangered species					
	Forest increment and fellings					
	Soil erosion					

Table 5
Trend-based environmental sustainability performance of Norway, 2007–2011. (For interpretation of the references to color in this table, the reader is referred to the web version of this article.)

Theme	Indicator	2007	2008	2009	2010	2011
Energy performance	Carbon intensity of heat and electricity generation					
	Energy intensity of economic activity					
Waste management	Total volume of municipal waste generation					
	Waste sent to landfill					
Air quality and pollution	Total emissions of PM 2.5					
	Total emissions of PM 10					
	Total emissions of carbon monoxide (CO)					
	Carbon intensity of economic activity					
Water quality and pollution	Fresh and groundwater abstraction					
	Wastewater treatment					
Land use, agriculture and fisheries	Pesticide use					
	Fertiliser consumption					
	Sustainability of fish stocks					
Biodiversity, forests and soil degradation	Endangered species					
	Forest increment and fellings					
	Soil erosion					

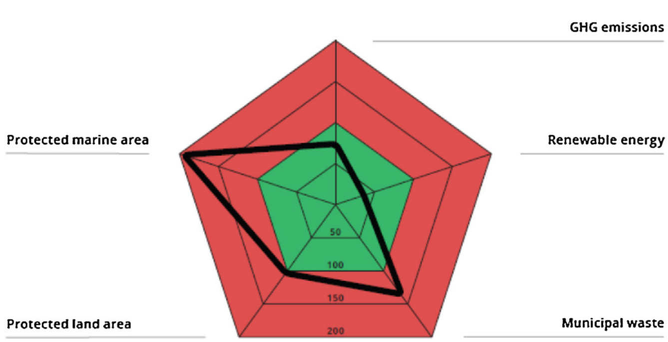


Fig. 17. Iceland – performance versus environmental sustainability targets (2011).

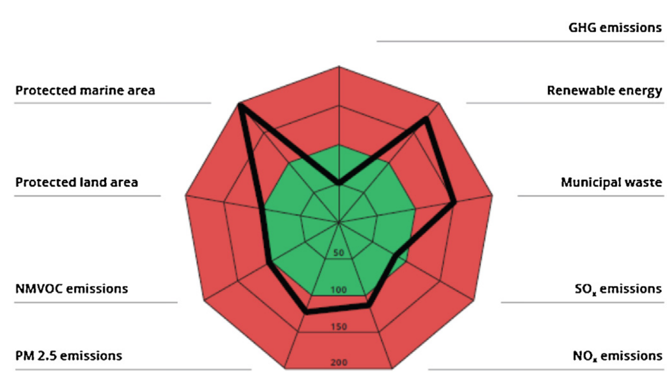


Fig. 18. Norway – performance versus environmental sustainability targets (2011).

in Tables 4 and 5 below. Note that in the case of Iceland, the carbon intensity of heat and electricity generation is close to zero for the years 2008–2011 inclusive, and thus performance is denoted via a green traffic light despite no improvement to the rolling three-year average.

In the case of Iceland, there are seven indicators for which no data was available, and thus these are marked entirely in grey to denote missing values. In the period 2007–2011, there has been a consistent increase in Iceland's energy intensity of economic activity and the total emissions of sulphur oxide, most of which has derived from hydrogen sulphide connected to the expanded use of geothermal resources for electricity production. Progress is evident in the declining volume of waste destined to landfill sites, while the carbon intensity of heat and electricity generation is exemplary throughout.

Norway's chart reveals burgeoning energy consumption and increased carbonisation of heat and electricity generation. The total volume of municipal waste has tended to increase while the proportion destined for landfill has headed in the opposite direction. As per the case with the target-based indicators, Norway continues to make excellent strides in reducing its emissions of air pollutants.

5.2. Strengths and limitations of the methodology

The methodology proposed in this paper provides a clear and transparent basis for appraising the often complex environmental sustainability performance of Nordic nations. In contrast to existing environmental performance indices such as the EPI, which use generic targets to appraise performance, the focus of this approach has been to use common indicators of environmental performance, wherever possible, with nation-specific targets. Thus, the method moves beyond a criteria-by-criteria comparison between nations, and reflects instead the particular situation within a nation from which environmental progress must be commenced. Wherever performance targets for particular indicators are identical across nations, the method still retains utility in terms of direct comparison. The use of two different methods of summary analysis – radar charts for indicators with numeric targets and a traffic-lights system for trend-based indicators – enables performance to be comprehended over time, helping to facilitate the instigation of new policy initiatives to improve or further drive progress towards more environmentally sustainable outcomes.

In terms of the practical application, accuracy and usefulness of the method, the case studies and summary analysis reveal three key problems related to the measurement of environmental sustainability in a Nordic context: (1) data availability; (2) availability of suitable indicators; (3) suitability and relevance of policy targets.

As well as providing a very easy-to-understand snapshot of trend-based indicator performance over time, the traffic-lights analysis in Tables 4 and 5 also identifies considerable gaps in data for key criteria. In the case of the sustainability of fish stocks indicator, there is not merely a data shortage but an absence of a suitable existing metric that can be utilised (Pauly et al., 2013). This is particularly surprising given the increasing availability of data in recent decades concerning catch data and scientific assessments of trends in fish abundance. One option for a future indicator could be to assess the proportion of fish stocks that are managed sustainably. This indicator could then be linked to Strategic Goal B, Target 6 of the Aichi Biodiversity Targets, requiring, by 2020, all fish and invertebrate stocks and aquatic plants to be managed and harvested sustainably (CBD, 2016).

Other areas where data availability was sparse or non-existent for both Iceland and Norway concern the indicators relating to endangered species, soil erosion, fresh and groundwater abstraction, and forest increment and fellings. For both Iceland and Norway, data on biodiversity-related indicators has so far been gathered only once by the Convention on Biological Diversity using their current assessment method. In the case of soil erosion, this is known to be a considerable problem in Iceland, yet the only national appraisal of this affliction dates from 2001 (Arnalds, 2001). In observing these omissions, it is evident that a complete measurement of environmental sustainability for these two Nordic nations is not yet possible. Rather than detracting from the method itself, this limitation highlights the need for much broader and more regular data collection across a variety of environmental domains at the national tier of analysis. Moreover, it must be recognised that the occasional use of proxy indicators in the Nordic set equated to a substandard approach of substitution. This is not to say that indicators relating to municipal waste generation and recycling are unimportant in their own right, but they can only provide the merest approximation of possible outcomes relating to the much greater volume of waste associated with total national waste generation.

Wherever national or European-determined targets existed for particular indicators, these were preferred to trend-based objectives. Both approaches have merit, but typically legally enshrined policy targets are more effective at driving the necessary institutional and technological change to lead to environmental improvements. Critics of the proximity-to-target approach might contend that the use of targets reflects not what is environmentally sustainable as an objective, but what is politically feasible (Moldan and Dahl, 2007). This contention clearly has some merit as environmental targets are historically prone to political satisficing. Do the Aichi targets for the protection of land and marine habitats even reflect a minimum standard for environmental sustainability in a biodiversity context? Are the Kyoto targets reflective of environmental sustainability when the atmosphere is a global public good and they are focused on a small percentage of global greenhouse gas emissions? However, in forming this paper's indicator set, the aim has not been to review the quality of agreed environmental targets. Irrespective of their quality as ultimate beacons of environmental sustainability, they still act as a litmus paper of progress towards improved environmental outcomes. Moreover, the utility of this paper's method is greatly reduced if it operates outside the scope of pre-existing policy standards. This paper aimed, therefore, to use established targets as instigators in a long-term iterative process of continual performance improvement, to be driven via future revisions to national policies that reflect more stringent standards. The widespread availability of annual data for all indicators of environmental sustainability is critical to fulfilling this objective.

Care is necessary in interpreting indicator outcomes where targets are not directly relevant to the year of assessment. For instance, under the Gothenburg Protocol, Norway was required to meet a target for total emissions of NMVOC of 195 thousand tonnes in 2010. In 2011, the country commenced progress towards meeting the more stringent target of 132 thousand tonnes, to be achieved by 2020. In this paper, Norway has been determined to be failing in meeting its 2020 requirements for emissions of NMVOC, as this highlights a need for new policy initiatives to deliver environmental progress. However, practitioners may consider Norway's assessment to be fairer if they arbitrarily apply incrementally more challenging targets in the period 2011–2020, culminating in the eventual target of 132 thousand tonnes only in the final year of assessment.

5.3. Application of the indicator set to other national contexts

The geographic, economic, social and cultural issues common to the Nordic nations of Iceland and Norway ensure that the use of a single indicator set is particularly useful for measuring the environmental sustainability performance of each of the these nations. The application of this paper's general method to other national contexts has considerable merit, albeit the successfulness of its implementation will rely greatly on the familiarity of the expert team with the particular countries assessed and data availability. In very different regional contexts to the Nordic region, it will be necessary for other expert teams to conduct focus group sessions, using this information to consider a pool of potential indicators, and then applying the same evaluative criteria as in this paper to determine their respective suitability. Developing countries often tend to face a somewhat different set of environmental challenges that are influenced much more by issues related to survival and health, such as access to clean water, access to sanitation, and avoidance of drought. However, the method set out in this paper has sufficient flexibility to provide a holistic appraisal of any nation's environmental sustainability performance, especially through its insistence, wherever practicable, on the use of nation-specific targets to assess outcomes.

6. Conclusion

Measuring environmental sustainability is a challenging endeavour that requires careful evaluation of a broad array of environmental criteria. Whereas existing indices seek to measure and compare environmental performance between nations and according to highly-popularised ranking lists, this paper's methodology focused specifically on the creation of a core indicator set retaining relevance to a nation-specific context. Applying focus group interviews, expert judgment and a rigorous five-stage process to indicator selection, a set of 23 final indicators were selected from an initial pool of 30 options. Indicators were selected according to their overall adherence to five key criteria: policy relevance, utility, soundness, interpretability, and data availability and quality. The case studies of Iceland and Norway were used to sketch out an analytical approach that will subsequently be applied and greatly extended in another paper to cover the main factors affecting performance across each of the Nordic nations. Use of different evaluative techniques to summarise progress according to target or trend-based objectives – radar charts and traffic-lights respectively – provided a means of communicating performance in an easily-understood manner. Both evaluative approaches suggested areas where new policy initiatives may be necessary in Iceland and Norway to correct for regress or drive forwards towards more stringent standards. Data shortages currently prevent an appreciation of national performance over time related to the issues of biodiversity, fisheries, soil erosion, and groundwater abstraction.

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3. Paper II: Energy projects in Iceland – advancing the case for the use of economic valuation techniques to evaluate environmental impacts

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Energy projects in Iceland – Advancing the case for the use of economic valuation techniques to evaluate environmental impacts

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HIGHLIGHTS

- Current risk of sub-optimal decision-making by licensing body, Orkustofnun.
- OECD call for monetary valuations of environmental impacts linked to Icelandic energy projects.
- Lessons to be learned from US regulatory approach to advance cost-benefit assessment practice in Iceland.
- Practice of conducting non-market valuation techniques limited in Iceland, but now growing.

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ABSTRACT

Decision-making in Iceland has occurred without reference to economic valuations of the environmental impacts of energy projects. Environmental Impact Assessments, a legal requirement for nearly all energy projects in Iceland since 1994, have played an important role in identifying the environmental impacts of energy projects, and proposing mitigation measures. However, a purely qualitative description of environmental impacts is insufficient to ensure that they are accounted for equivalently with all of the other costs and benefits of a proposed project. Instead, as monetary information concerning the welfare gains or losses of proposed projects is not currently required to be provided to the licensing body, Orkustofnun, there is the potential for sub-optimal decision-making to occur. As this paper sets out, a broad variety of non-market valuation techniques already exist and could be applied to estimate the value of environmental benefits sacrificed to accommodate such developments. These methods and their outcomes could be incorporated within mandatory cost-benefit assessments for proposed Icelandic energy projects, communicating an estimate of the full welfare implications of approvals to decision-makers and the public alike, and fulfilling an OECD demand for the country to commence such processes.

1. Introduction

The objective of public policy is to improve or correct components of social welfare, from economic conditions to health to the quality of the environment (Lazo and McClain, 1996). Approving development projects with significant environmental impacts implies that the forgone benefits are expected to be less than a project's financial gains. A broad variety of non-market valuation techniques exist for estimating derived environmental benefits, yet in the absence of such valuations to guide decision-making, projects may be approved which result in a net loss in social welfare (Pearce, 1998; Dixon et al., 2013). This risk is evident in the case of Iceland, where neither the cost-benefit assessments (CBA) for renewable energy power plants nor industrial works reliant on their generating capacity have been required to incorporate such non-market considerations.

Iceland has become a world-leader in terms of harnessing renewable energy, with its abundant hydropower and geothermal sources together now supplying almost 100% of electricity generation and 85% of primary energy use (Orkustofnun, 2014). The availability of highly competitive energy prices and a secure supply of electricity have led to an expansion in the number of power plants and the role of energy-intensive industries, particularly aluminium smelting, which consumes 68.40% of the nation's annual electricity consumption (Orkustofnun, 2014). Unable currently to export Iceland's renewable energy abroad, this focus has been effective in drawing in foreign investment and diversifying the export industry (Kristófersson and Cosser, 2009), but has also

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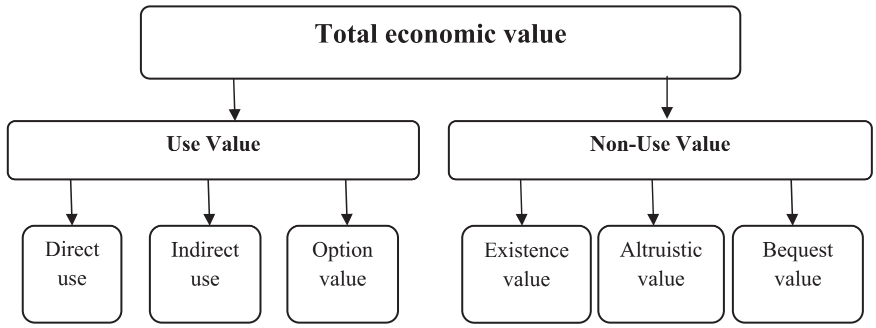

Fig. 1. Total economic value framework.

led to burgeoning environmental impacts such as a 178% increase in the leakage of sulphur hexafluoride (SF_6) emissions from electrical equipment in the period 1990–2013 (NIR, 2015). The Global Warming Potential of SF_6 emissions is around 3400 times greater than an equivalent volume of carbon dioxide.

Since 1994 the qualitative nature of environmental impacts related to proposed energy projects have been outlined within mandatory Environmental Impact Assessments, but no effort has been made to quantify these effects in monetary terms to be compared against the economic gains of projects. This is despite 'Welfare for the Future – Iceland's National Strategy for Sustainable Development 2002–2020′ setting out a strategic objective for the country to *"introduce more economic instruments in the field of environmental protection and resource utilisation in the near future"* (Ministry for the Environment in Iceland, 2002, p. 13). Moreover, the OECD has repeatedly requested that Iceland commences accounting for environmental impacts within decision-making (OECD, 1993; OECD, 2001; OECD, 2014). Most recently, the OECD's (2014) assessment reiterated that it was important for Iceland to *"develop some cost-benefit analysis process which gives appropriate consideration to all dimensions of power development (environment, tourism, social and regional development, project profitability)"* (OECD, 2014, p.115).

The aims of this paper are to review the current decision-making basis in Iceland in relation to energy projects, in so doing setting out the rationale for conducting valuations of the environmental benefits sacrificed as a consequence of developing Iceland's energy resources. Section 2 begins by discussing environmental benefits in terms of the broad concept of ecosystem services. This concept is then linked to the total economic value framework, before a review is carried out concerning the strengths and weaknesses of the various non-market valuation techniques that can be applied to estimate the various value components. Section 3 provides a summary of the national policy, regulatory and legislative context in Iceland relevant to energy projects, before delineating the changes necessary to ensure that environmental impacts are properly accounted for in decision-making, as per the OECD's clarion call. Finally, Section 4 outlines the methodology pertaining to the upcoming contingent valuation studies concerning two of Iceland's geothermal areas (Hverahlíð and Eldvörp), in so doing highlighting one possible approach to valuing the environmental implications of a future Icelandic energy project.

2. Total economic value and economic valuation techniques

2.1. Introduction to ecosystem services and the concept of total economic value

2.1.1. Ecosystem services and utilitarian conceptions of value

The value of the many benefits deriving from natural resources – their ecosystem services – can be expressed in different ways according to cultural conceptions, philosophical perspectives, and schools of thought (Goulder and Kennedy, 1997). Ecosystem services are commonly classified into four categories: (1) provisioning, such as the production of food or reaping of a timber harvest; (2) regulating, such as climate control or water filtration; (3) supporting, such as pollination and nutrient recycling; and (4) cultural, such as spiritual and recreational benefits (MEA, 2005). One of the main endeavours of the Millennium Ecosystem Assessment was to evaluate the importance of ecosystem services to human welfare, so as to help promote more informed decisions concerning the management of natural resources (MEA, 2005). From a purely anthropocentric perspective, ecosystems have value because they provide services to sustain life and satisfy the consumption demands of human beings (Costanza et al., 1997). Such a perspective relies on a utilitarian conception of value, whereby human beings source utility from ecosystem services either directly or indirectly. The overall level of utility from an ecosystem service requires the aggregation of individual preferences and an indirect form of estimation using the metric of money. That is not to say that only ecosystem services generating monetary benefits are considered in economic valuation techniques. Rather, the majority of economic assessments are focused on non-market valuation techniques that estimate utility indirectly using this metric.

2.1.2. Ecosystem services and the total economic value framework

A commonly used framework for examining the utilitarian value of ecosystem services is the concept of total economic value, an all-encompassing measure of the economic value of any environmental resource. Economists have typically split the total economic value of natural resources into two main constituent parts: use and non-use value (Tietenberg, 1988; Hanley, Shogren and White, 2013), as summarised in Fig. 1.

Use value includes direct use, indirect use and option value (Bateman and Willis, 2001). In the case of direct use value, individuals undertake a planned demand for an ecosystem service. This may take the form of consumptive use, whereby individuals extract provisioning services from an ecosystem. Alternatively, direct use may be non-consumptive in character and not involve a drawing down on resource stocks, such as during the receipt of cultural, spiritual and recreational benefits. Consumptive forms can generally be traded in a market while non-consumptive cannot.

Indirect use value broadly relates to the MEA's depiction of regulating and supporting ecosystem services. Although they are frequently ignored as individuals do not receive direct benefits, these services are integral to the survival of life on the planet, including key functions such as climate regulation, waste assimilation, nutrient and water cycling, pollination, and pollution filtering (Mitchell and Carson, 1989).

Option value refers to the possibility to gain utility from a resource in the future, either directly or indirectly (Weisbrod, 1964; Hanemann, 1989). Although an individual has no immediate intention to gain utility from a particular resource, their option value relates to an opportunity to do so in the future.

Non-use value, also sometimes referred to as existence value or passive value, is derived purely from the knowledge that a resource is preserved (Krutilla, 1967; Hanley et al., 2013). The three main components are existence value, altruistic value and bequest value. Existence value describes the utility individuals gain from the existence of a resource, despite no intention to demand its ecosystem services, now or in the future. Altruistic value relates to the utility sourced from knowing that other individuals can use a resource. Bequest value is similar to altruistic, but relates to the utility acquired when individuals believe that a resource will be preserved and available for use by future generations.

2.2. Valuation methods and techniques

2.2.1. Cost benefit assessments and total economic value

The aim of this paper is not to provide a review of the theoretical foundations of CBA, however, a few very brief aspects should be pointed out with regards to its framework. CBA involve a calculation of the aggregate monetary costs and benefits of often many projects or policies, aiming to establish the option with the greatest surplus in benefits. Economic benefits are considered to be utility generating and thus increase human economic welfare, while costs have the opposite effect (Pearce and Nash, 1981). All benefits and costs are discounted according to the time value of money concept to ensure a common 'net present value' basis for their comparison. For projects where the aggregate discounted benefits exceed aggregated discounted costs, a welfare gain to society accrues.

In terms of decision-making, where the impacts of ecosystem management decisions are presented in purely physical, qualitative terms – such as in an Environmental Impact Assessment – a considerable layer of subjectivity can cloud the debate concerning the merits of economic utilisation versus preservation of environmental resources (Dixon et al., 2013). Although CBA can provide a standardised means of evaluating the benefits and costs of projects and policies, distorted welfare outcomes will result if studies fail to capture all of the costs or benefits of a project or policy, including environmental impacts such as the loss of or change in quality of ecosystem services (Atkinson and Mourato, 2008; Koundouri et al., 2009; Dixon et al., 2013). Failure to do so results eventually in an implied valuation of environmental resources by virtue of the outcomes arrived at by decision-makers (Navrud, 2001).

2.2.2. Non-market valuation methods and techniques

Based on the utilitarian conception of value underlying the foundations of CBA, the purpose of non-market valuation techniques is to estimate the value of ecosystem services by ascertaining individual preferences through the common, easily understood metric of money (Champ et al., 2003; Freeman, 2003; Dixon et al., 2013). The various techniques are generally split according to whether they are either revealed or stated preference methods.

Revealed preference methods involve the gathering of data concerning individual preferences for marketable goods related to the non-market good. The approaches assume that consumer behaviour is always rational and seeking to maximise utility, and that actual preferences can be revealed by the direct observation of responses to complement or substitute goods. The techniques include market pricing (Harris and Roach, 2013), avoided cost (Hanley et al., 2009; Harris and Roach, 2013), replacement cost (Hanley et al., 2009; Harris and Roach, 2013), production function approaches (Pattanayak and Kramer, 2001; Harris and Roach, 2013), hedonic pricing (HP) (Tyrväinen , 1997; Harris and Roach, 2013), and the travel cost method (TCM) (Mitchell and Carson, 1989; Fleming and Cook, 2008; Harris and Roach, 2013).

Stated preference methods rely on the use of carefully designed questionnaires to elicit individual preferences for a change in the level of provision or quality of an environmental resource. The main techniques are the contingent valuation method (CVM) and discrete choice experiments (DCE). Unlike revealed preference methods, which can be applied to estimate use value, the CVM and DCE can also be used to estimate non-use value. The CVM is an advanced survey-based technique that has been applied to a broad variety of environmental contexts to elicit valuations of non-market goods (Mitchell and Carson, 1989; Hanemann, 1994; Venkatachalam, 2004; Carson, 2012; Harris and Roach, 2013). DCE are a particular variant of the CVM and presents participants with at least two different possibilities concerning the set of future attributes of a site (Carson and Louviere, 2012).

Table 1 summarises the general strengths and limitations of the respective economic valuation methods in the context of specific ecosystem services and the total economic value framework.

2.3. Choosing methods to estimate total economic value and likely challenges in Iceland

Each of the non-market valuation methods comes attached with specific strengths and limitations, and the choice of techniques depends greatly on the ecosystem services appraised. It is clear that when estimating the total economic value of environmental resources, a number of methods may be needed, and their choice depends greatly on the services being valued, context, and the available resources – financial and time – of research teams. However, it is likely in all cases that stated preference techniques will need to be adopted as they are the only means of estimating non-use value, and a large number of studies have highlighted the potential significance of this component, especially for sites with limited recreational value (Sorg and Nelson, 1987; Lee and Han, 2002; Freeman, 2003; Hanley et al., 2009; Hoyos et al., 2012; Tentes and Damigos, 2012; Koundouri et al., 2014).

In an Icelandic context, the non-use value associated with preserving potential hydro power and geothermal sites may represent a considerable proportion of total economic value, especially for any future energy projects relying on hydro power resources located in the nation's remote and uninhabited central highland region. When carrying out stated preference methods for any potential geothermal or hydro power project located outside of Reykjavik, it will be challenging for researchers to determine the affected population to survey, as sites may have either a regional, national or even international resonance. Approximately two-thirds of the national population are located in Reykjavik, with the remainder very widely dispersed. Researchers will therefore need to make use of pre-existing online panels to ensure they gather representative samples of their deemed affected population.

For likely forthcoming geothermal power projects, such as Hverahlíð and Eldvörp (Rammaáætlun, 2011), current evidence concerning visitor numbers is perceived largely on an anecdotal basis rather than deriving from year-round data. The recreational value of these areas throughout the year is uncertain and where the time and financial resources of research teams permit, the upcoming results from continent valuation studies of these sites should ideally be bolstered through travel cost studies based on

Table 1
Economic valuation methods for different ecosystem services – main strengths and limitations.

Valuation Method	Elements of total economic value captured	Ecosystem service(s) valued	Strengths of approach	Limitations of approach
Revealed preference				
Market pricing	Direct and indirect use	Provisioning services	Market data reflects individual WTP based on observed behaviour for goods and services exchanged in markets Data is relatively easy to obtain for specific provisioning services.	Market data may not be available for the services provided by an environmental resource. Where markets do exist, the price may not reflect the service's true economic value due to market imperfections, such as externalities of production.
Replacement or avoided cost	Direct and indirect use	Regulating and supporting	Methods can convey an approximation of economic value broadly consistent with the economic concept of use value.	The method assumes that costs – either replacement or avoided – are a valid proxy for estimating benefits. The approach fails to consider social preferences for ecosystem services or individual preferences in their absence.
Production function	Indirect use	Provisioning, regulating and supporting services acting as inputs to market production	A relatively straight-forward methodology in theory, based on actual market behaviour.	The approach is limited in practice to the resources that are used as inputs to marketed goods. Biophysical links between the quality/quantity of the ecosystem services and their contribution to the price of the marketed good are poorly understood.
Hedonic pricing	Direct and indirect use	Commonly supporting and cultural services providing attributes of value to buyers	Method estimates values according to actual purchases, typically related to property markets and the vector of characteristics potentially influencing price. Data on property markets and the characteristics influencing price are generally available.	Generally a method limited to estimating values related to property markets. Method is data-intensive and takes time to analyse, involving complex statistical techniques. Not all environmental influences on housing prices are necessarily captured by the statistical model.
Travel cost method	Direct and indirect use	All ecosystem services contributing to recreational activities	Results are based on actual economic behaviour in surrogate markets. Generally straight-forward to collect a large sample size through on-site sampling.	Method is limited to capturing use components of total economic value and cannot be used alone to estimate the total economic value of an environmental resource. Method assumes that individuals respond to changes in travel costs in the same manner that they would to changes in admission prices. Many travel cost models fail to accommodate trips made with multiple purposes in mind, thus overestimating recreational benefits. The availability of substitute recreational sites affects value, as for two trips of identical cost, the one of greatest value relates to the site with most substitutes in its vicinity. The individuals that most value a site may choose to live closest, and will therefore have very low travel costs, resulting in a considerable underestimate of their true benefits.
Stated preference				
Contingent valuation method	Use and non-use	All ecosystem services	A very flexible method that can be used to measure all components of total economic value, either individual components or in aggregate. Method has been widely adopted and is very appropriate in cases where limited or no observed behaviour exists to estimate the total economic value of an environmental resource or its specific ecosystem services through other methods. Although poorly conceived surveys are very prone to bias, a number of best practice guidelines have been developed in recent years to ameliorate this risk, particularly the NOAA panel report by Arrow et al. (1993).	Criticisms in the academic literature have typically related to observations of hypothetical, starting-point and strategic sources of bias, as well as information and eliciting effects (Duffield and Patterson, 1991; Kahneman and Knetsch, 1992; Diamond and Hausman, 1994; Hausman, 2012). Method assumes that participants are able to understand the provided scenario and have an economic value for the good in question – many individuals are not be familiar with placing an economic value on environmental goods and services.

Table 1 (*continued*)

Valuation Method	Elements of total economic value captured	Ecosystem service(s) valued	Strengths of approach	Limitations of approach
Decision choice experiments	Use and non-use	All ecosystem services	Participants are required to consider trade-offs in terms of policy or project outcomes, which may be easier to contemplate than a WTP/WTA estimate in a contingent valuation study. As the prices of different alternatives are provided for participants rather than elicited, some of the information and eliciting effects commonly reported as afflicting the CVM are not so applicable. In a strategic sense, relative value estimates obtained from DCE may also be more valid than absolute monetary valuations, ensuring their usefulness in making policy decisions.	Not all of the potential trade-offs of project or policy options will necessarily be described to participants and thus participants may make choices that they would not make if these alternatives had not been presented to them. Preferences for certain trade-offs may be difficult to evaluate, particularly if bundles of characteristics are unfamiliar to participants. The hypothetical and strategic sources of bias affecting the CVM can be equally relevant in the case of DCE.

seasonal demand data. Acquiring such information may be particularly challenging given the remoteness, harsh climate and frequent inaccessibility of many areas outside of Reykjavik during the winter months. In addition, scientific research needs to be commenced in Iceland to determine the range and spatial scale of ecosystem services provisioned at undeveloped energy sites, particularly the provisioning and regulating types associated with geothermal resources. In the absence of this knowledge it will be impossible for researchers to even begin to apply revealed preference techniques to estimate the contribution that these services make to total economic value.

3. Energy projects in Iceland, planning policy and regulatory context

3.1. Energy resources and consumption in Iceland

During the course of the 20th century Iceland transitioned from a nation heavily reliant on imports of coal and kerosene for heating and cooking to a largely self-reliant energy system, one which harnesses abundant domestic renewable energy resources. In recent years the demands of power-intensive industries (particularly aluminium smelting) have led to a considerable expansion in low-cost electricity production. Iceland has become the world's largest electricity producer per capita, generation that has almost entirely derived from renewable energy sources (OECD, 2014). Renewable energy production accounted for 99.9% of the 18,116 GWh of electricity generation in 2013 – 12,863 GWh (71.0%) from hydro power and 5245 GWh (28.9%) from geothermal, with very small contributions of 3 GWh and 5 Gwh from fossil fuels and onshore wind energy respectively (Orkustofnun, 2014). In 2013, Iceland consumed a total of 251.4 Petajoules (PJ) of energy, of which 217.0 PJ (86.3%) was generated domestically from renewable energy sources – 170.7 PJ (67.9%) from geothermal energy and 46.3 PJ (18.4%) from hydro power (Statistics Iceland, 2015). The remaining 34.4 PJ (13.7%) of energy consumption derived from imported fossil fuels, predominantly for use in motorised transport and ships – 30.4 PJ from oil (12.1%) and 4.0 PJ (1.6%) from coal (Statistics Iceland, 2015).

3.2. National energy policy in Iceland

As a member of the European Economic Area (EEA) since 1994, Iceland has constructed its legislative framework and policy agenda to fulfill all relevant EU legislation common to the EEA agreement, including Directive 2009/28/EC of the European Parliament on the promotion of the use of renewable energy sources. In order to satisfy the objectives of Directive 2009/28/EC and respond to anticipated growth in gross national energy consumption of 1067 ktoe (49.3%) between 2005 and 2020 (Ministry of Industries and Innovation, 2012), the Icelandic National Renewable Energy Action Plan was formed in 2012.

Iceland has already met the main target set by Directive 2009/28/EC for at least 72% of the nation's primary energy demand to be satisfied using renewable energy generation by the year 2020. However, despite relatively limited reliance on fossil fuels compared to other European nations, in order to ensure compliance with a challenging government goal for 10% of energy demand in the transport sector to be from renewable energy sources by the year 2020 – in line with Directive 2009/28/EC's stipulations – further expansion in renewable energy generation will be required, especially in motorised transport.[1] There remain sources of

[1] In 2011 only 0.35% of energy demand in the transport sector derived from

hydro power and geothermal energy in Iceland yet to be tapped (Rammaáætlun, 2011), while early trials of onshore wind energy have been more productive than expected (Landsvirkjun, 2015).

3.3. Strategic planning – master plan for hydro and geothermal energy resources in Iceland

In the period between 1970 and 1990 there was gradual political recognition in Iceland that a range of interests need to be considered in terms of the impacts of harnessing the nation's renewable energy resources. During this time, a committee of specialists from the Ministry of Industry, National Energy Authority (Orkustofnun), National Power Company (Landsvirkjun), and the Nature Conservation Council met regularly to discuss various power plant plans, with particular attention given to their environmental impacts (Ketilsson et al., 2015). A political view began to emerge which recognised that there was merit to having a strategic guide to aide decision-making concerning energy projects, an opinion that was further reinforced following the enactment of Environmental Impact Assessment legislation in 1994.[2] In 1997, the Government proceeded to issue a white paper on sustainability in the Icelandic society (Thórhallsdóttir, 2007b). This document stressed the need for the development of a long-term Master Plan, categorising and ranking energy projects according to their likely economic, environmental and social impacts (Ketilsson et al., 2015).

Akin to a form of Strategic Environmental Assessment in terms of its land use planning objectives, the development of the Master Plan commenced in 1999 and was enshrined in Icelandic law in 2013,[3] in so doing becoming one of the world's most comprehensive national-level strategic guides for the sustainable use of energy resources. Rather than evaluating the level of detail required to complete an Environmental Impact Assessment, its aim was to provide a broad overview of the various potential hydro power and geothermal energy projects, ranking these according to their particular environmental, socio-cultural and economic impacts (Thórhallsdóttir, 2007a, 2007b). A Steering Committee was responsible for coordinating the activities of four separate working groups to assess the many impacts of energy projects – the first considered environmental impacts and cultural heritage; the second dealt with recreation and land use impacts; the third reviewed regional and economic consequences; and the fourth examined likely energy capacity and project costs. In the case of the first working group, two criteria were used as general guidelines for determining impacts: Article 1 of the Nature Conservation Act (Law 44/1999) and Article 1 of the National Heritage Act (Law 107/2001). The former stressed that Icelandic nature should be developed according to its own laws and the protection of what is unusual or historically important; the latter safeguarded Icelandic cultural heritage, placing emphasis on the retention of in-situ archaeological monuments. Values and impacts for each of five defined environmental classes were scored by Working Group 1 on a non-linear four-point numeric scale (1=insignificant impacts; 3=some; 6=large; 10=very significant) against six attributes: diversity and richness; rarity; size in area, completeness and pristineness; information (epistemological, educational, typological and scientific) and symbolic value; international responsibility; and scenic value (Ketilsson et al., 2015). The average score for each environmental class was weighted (not equally) and aggregated to arrive at an overall score for each project's environmental impact. By the end of two phases of analysis in 2011 and following the compilation of the scores from the four working groups, the eventual Master Plan approved by the Icelandic Parliament ranked 35 hydro power and 32 geothermal projects respectively – 16 (2 hydro power, 14 geothermal) were then classified as 'suitable for development' and 20 (11 hydro power, 9 geothermal) were considered to be 'protected', while the remaining 31 (22 hydro power, 9 geothermal) projects bracketed as 'under consideration' pending further data and review (Rammaáætlun, 2011). Further projects are currently being evaluated during the third phase of the Master Plan, including sites for potential onshore wind energy utilisation, and this process is due to complete in 2017.

3.4. Review of regulatory and decision-making requirements for new energy projects

Licenses for Icelandic power projects involving the utilisation or exploration of resources are granted by Orkustofnun, a legally independent government agency operating under the auspices of the Ministry of Industries and Innovation. Orkustofun's responsibilities, as set out in the Act on Orkustofnun (87/2003), also involve the provision of information and research concerning energy matters in Iceland, together with regulation of the main acts governing natural resource exploration and licensing activities.

No proposed power project can receive a license from Orkustofnun in the event that it is located in an area categorised for protection or pending further research as per the legally binding Master Plan. Secondly, assuming a project is deemed suitable for development by the Master Plan, Orkustofnun carries out decision-making concerning the award of licenses having ascertained that all survey, utilisation and power production proposals are legally compliant, particularly with respect to the Planning and Building Act (73/1997), Resources Act (57/1998), Nature Conservation Act (44/1999), Environmental Impact Assessment Act (106/2000), Electricity Act[4] (65/2003), and Water Act (20/2006).

The Resources Act establishes the legal standards with regards to the exploration, ownership and utilisation of all natural resources in the ground, bottom of rivers and lakes, and the seabed within netting limits, covering all geothermal energy resources and surveys of hydropower for the generation of electricity. While previously the Minister of Energy granted licenses for energy utilisation for periods of up to 65 years, in 2008 the Icelandic Government opted to add a clause into the Resources Act stating that this responsibility now came under the remit of Orkustofnun. The Minister continues to retain a decision-making role in the event of an appeal. The Electricity Act sets out provisions and rules with regards to electricity production and transmission, distribution and matters of trade. The Water Act has the objective of ensuring the clear ownership of water resources, as well as their efficient and sustainable use. Provisions include items with respect to property rights, priority of access, and the utilisation of hydro power and expropriation.

The Nature Conservation Act establishes the broad legislative basis for the sustainable management of the environment in Iceland, regulating interactions between man and natural resources to prevent neither harm to the bio-sphere or geo-sphere nor pollution to the air, sea or water. Article 21 of the Resources Act asserts that the Nature Conservation Act also applies with respect to geothermal areas being surveyed and utilised. The

(*footnote continued*)
renewable energy sources (Ministry of Industries and Innovation, 2012; Ketilsson et al., 2015).

[2] Iceland joined the European Economic Area in 1994 and was required to adopt the European Directive EIA85/337 on environmental impact assessment. This came into effect in 1994 and has since been amended twice, in 2000 (Law 106/2000) and 2005 (Law 74/2005).

[3] Law number 48/2011: http://www.althingi.is/lagas/141b/2011048.html.

[4] Licenses for electricity production are not generally required for projects of less than 1 MW.

Environmental Impact Assessment Act ensures that prior to decision-making concerning projects deemed to have the potential to cause considerable environmental and social impacts, a comprehensive qualitative assessment of their proposals is undertaken to characterise these effects. All major power project proposals and those related to power lines are required to carry out an Environmental Impact Assessment in accordance with the stipulations of the Act,[5] which must include the preparation of a list of design improvements to mitigate environmental impacts. Administration and implementation of the Act is the responsibility of the National Planning Agency (Skipulagsstofnun), who, once the final EIA is published, issues a non-binding opinion on the project.

3.5. A regulatory gap – the case for economic valuations of sacrificed environmental benefits

Reliant on a complex mix of scientific analyses by experts and public consultation, the Master Plan represents a considerable step forwards in terms of improving the strategic basis via which the suitability of potential Icelandic energy projects is determined. Furthermore, its determinations, formed using expert input sourced from multiple disciplines, help to move the country towards some sort of a consensus concerning complex energy-environment issues. However, there remain some obvious procedural and technical deficiencies that should be addressed when the next iteration of the Master Plan is published in 2017.[6] These include shortcomings connected to the lack of data for some criteria, particularly environmental aspects pertaining to the development of geothermal resources, such as wastewater and air pollutants. In addition, there is a need for greater transparency of process and outcome as it has been contended that it is too easy for projects to be shifted from one classification category to another – allegations were levied that the Master Plan's steering committees were not independent and that rankings were changed at the end of the process for reasons of political ideology (Sæþórsdóttir, 2012). Monetising the environmental impacts of energy projects could eventually provide future iterations of the Master Plan with an evidence base for a better-informed weighting system, one that moves beyond the current arbitrary system.

Irrespective of the strategic suitability of projects for development, the role of the Master Plan is limited to the overarching, policy, planning and programming level; its task is not to identify the environmental and social impacts of proposed energy projects prior to decision-making, which requires the preparation of an Environmental Impact Assessment. Recent environmental controversies concerning energy projects in Iceland have appeared to highlight the limitations of EIA's in terms of their capacity to influence decision-making (Thórhallsdóttir, 2007b) – for example, particularly heated debate ensued concerning the environmental impacts of the 690 MW Kárahnjúkar Hydropower Plant in eastern Iceland, the largest such project in Iceland and used since 2007 to generate electricity for Alcoa's Fjardaál aluminium smelter in Reyðarfjördur. These impacts were predicted to be long-lasting and severe, diminishing both the landscape value of the area and biodiversity. They included permanent negative impacts to rare wildlife populations that were inhabiting, breeding and nesting in the affected area (particularly reindeer, pink-footed geese and harbour seals); widespread soil erosion; considerable hydrological changes leading to a reduction in groundwater flows and the creation of the Hálslón reservoir, which would destroy a rare highland vegetative area with considerable conservation value; and fragmentation and disruption of one of the last remaining wilderness areas in Europe, including the loss of one of Iceland's most well-known glacial canyons, Dimmugljúfur (Landsvirkjun, 2003).

It is evident that the approval of the Kárahnjúkar Hydropower Plant was indicative of weaknesses in regulatory and decision-making processes rather than EIAs per se. The EIA for the Kárahnjúkar Hydropower Plant led to the clear depiction of the numerous irreversible environmental impacts of the project, as well as the articulation of various mitigation measures. The regulatory deficiencies are twofold. Firstly, connected to power, it is evident that Skipulagsstofnun lacks the legal authority to reject developments when it deems environmental impacts to be unacceptable, as Orkustofnun can override their published opinions during final decision-making. To many, this was an evident feature of the process leading to the eventual approval of the Kárahnjúkar Hydropower Plant, as the scheme was originally rejected by Skipulagsstofnun on the grounds of the significant and irreversible environmental impacts set out in Landsvirkjun's EIA (Del Giudice, 2008; Newson, 2010). Secondly, and more critically, the determination of the acceptability of environmental impacts deriving from energy projects has the potential to become a highly subjective affair, never more so than when political willpower provides ballast to the vested interests of developers, many of whom will have already invested considerable capital by the time that their self-prepared EIA takes place (Benson, 2003; Wathern, 2013).

Any evaluative process involving the weighing up of negative qualitative data against monetary benefits instigates the risk that impacts related to the former have insufficient arbitrage in decision-making. Failure to also quantify these impacts in monetary terms can therefore lead to project approvals that undermine social welfare. Therefore, to ensure standardisation of all costs and benefits related to projects, by utilising the total economic valuation framework discussed in this paper and the most suitable non-market techniques, the Icelandic decision-making context could be strengthened considerably. During the planning phase for the Master Plan, the use of non-market valuation techniques was considered to estimate the value of the various resources. However, these approaches were rejected due to their prohibitively high cost and the logistical complexities of ensuring that stated preference techniques targeted a representative sample of affected populations (Thórhallsdóttir, 2007b). Conducting such techniques for all of the Master Plan's potential projects would certainly have been costly, time-consuming, and, above all, unnecessary. However, once detailed power plant proposals are available, such techniques can then be used to provide economic estimates of the value of environmental impacts. These outcomes can subsequently be used within cost-benefit assessments to ensure that a project's actual welfare gains/losses are evaluated alongside the qualitative impacts detailed in an EIA.

Although seemingly radical in an Icelandic decision-making context, the use of non-market economic valuation techniques within cost-benefit assessments is fairly commonplace in countries such as the US, at least in terms of regulatory analysis. They have also been applied in cases of costing natural resources damages, perhaps most prominently in the contingent valuation study pertaining to the Alaskan oil spill by Exxon Valdez in 1989 (Carson et al., 2003). In the US, the first cost benefit assessment of environmental regulations was carried out by the Environmental Protection Agency (EPA) to estimate the social benefits of reducing various pollutants. Cost benefit assessments have since become an entrenched part of the American regulatory process following the enactment of two key Executive Orders: 12,291 by President

[5] All project types listed in Annex 2 of the Act are required to carry out an EIA, including the drilling of production and research geothermal wells in high-enthalpy fields, all hydro power projects with output of more than 100 kW and geothermal heating production of at least 2500 kW.

[6] The next iteration will include new potential projects (including related to onshore wind) and the use of new data concerning the projects currently listed as 'under consideration'.

Reagan in 1981 and 12,866 by President Clinton in 1993. The former vested the Office of Information and Regulatory Affairs with the authority to review agency regulations and required government agencies to compile regulatory impact analyses on regulations with a likely impact of $100 million or more (Shapiro, 2011). Executive Order 12,866 affirmed that agencies must assess both the costs and benefits of the intended regulation and, when choosing among alternatives with different benefits-costs ratios, opt for the one with the greatest (Polasky and Binder, 2012). The US $100 million impact threshold has enabled scarce analytical resources to be directed towards regulatory changes with the greatest economic impact. In a way, Iceland's Master Plan already acts as an equivalent strategic screening mechanism by sifting out unsuitable energy projects. Of the projects deemed by the Master Plan to be 'suitable for development', only a fraction of these are likely to develop into full-scale proposals, as evidenced by the fact that over the past decade only four new power projects have commenced operations in Iceland.

In recent years the US has developed and continues to update its 'Guidelines for Preparing Economic Analyses' to ensure that the economic evaluation of regulations is transparent and not subject to arbitrariness. The guidelines focus on multiple analytical issues such as the suitability of various non-market techniques in different circumstances; how to estimate changes in environmental quality; defining baseline conditions; locating available data sources; and how to present the results of economic analysis (EPA, 2015). The development of a standardised approach to cost-benefit assessments is vital in order to ensure the transparency and consistency of the process. In the case of proposed Icelandic energy projects, Skipulagsstofnun, as per their remit with regards to EIAs, could develop and administer this guidance, and overview its implementation. Subsequently Orkustofnun would not be allowed to grant licenses to any proposed energy project that failed to pass the benefit-cost test, and in so doing Iceland would fulfill the OECD's oft-repeated demand for the nation to conduct such accounting practices. This would require the enactment of specific cost-benefit assessment legislation necessitating such assessments to be submitted in support of project proposals and carried out according to the designated approach permitted by Skipulagsstofnun. It is anticipated that some degree of consultation between developers and Skipulagsstofnun would be required on a project-by-project basis in order to determine the most appropriate non-market valuation techniques to be utilised.

4. Economic assessments of the value of natural resources in Iceland

4.1. History of non-market valuation studies in Iceland

Although the practice is common in some countries, in Iceland a mere handful of non-market valuations of the environment have been published so far: one hedonic pricing study concerning the value of Mount Esja (Jóhannesson, 2003), five contingent valuation studies (Ásgrímsdóttir, 1998; Bothe, 2003; Lienhoop and MacMillan, 2007; Ragnarsdóttir, 2010), and an economic valuation of ecosystem services relating to Lakes Elliðavatn and Vífilsstaðavatn (Jóhannesdóttir, 2010). Of these, all have been purely academic exercises and four of the studies have related to energy projects – Ásgrímsdóttir (1998) assessed the total economic value of an area proposed for a hydropower project in Skagafjördur, Bothe (2003) evaluated willingness to pay (WTP) to prevent the environmental impacts of the Kárahnjúkar hydropower project, Lienhoop and MacMillan (2007) assessed both WTP (willingness to pay) and WTA (willingness to accept) the environmental impacts of Kárahnjúkar, and Ragnarsdóttir (2010) estimated WTP for laying underground cables to prevent the visual impact of power lines.

4.2. Upcoming contingent valuation studies of Hverahlíð and Eldvörp

In cases where an environmental resource is perceived to be associated with limited recreational value and few or zero provisioning services, there can be considerable merit to using the CVM to estimate both use and non-use value, in so doing forming a stand-alone estimate of total economic value for use in cost-benefit assessments. In response to the OECD's oft-repeated demand to value economically sacrificed environmental benefits associated with developing Icelandic power projects, the authors of this paper will shortly be issuing contingent valuation surveys seeking to estimate the value of preserving the geothermal areas of Hverahlíð and Eldvörp.

The two areas differ considerably in terms of their environmental characteristics. Hverahlíð is located to the south-east of the existing Hellisheiði Power Plant – thirty minutes drive to the east of Reykjavík – and south of the busy road Suðurlandsbraut (Route 1). A proposed 90 MW power plant would impact an area including common, well-vegetated lava formations and hot springs in its geothermal locality. In visual terms, the area of Hverahlíð is perhaps less impressive than other geothermal areas nearby, and is perceived to have low recreational value, only being frequented on an occasional basis by hikers, horsemen, cross country skiers, and some tourists en route to other destinations further afield. Eldvörp is located on the Reykjanes Peninsula, approximately 45 km to the south-west of Reykjavík, and is estimated to have a productive capacity in the region of 50 MW. The area is characterised by course lava and a visually impressive 10 km long row of craters, which are believed to have emerged during the 'Reykjanes Fires' of 1211–1240. In addition to being a popular area for hikers with multiple trails winding their way through the crater row, a test well drilled in 1983 discovered evidence of human settlement, suggesting the site was once used as a hideout by outlaws.

Although the CVM has been subject to criticism over the years and Table 1 considers its common limitations, these can be largely overcome if studies pay careful attention to their sampling procedures and survey design, particularly through the clear setting out of a realistic scenario, well-defined scope for the good in question, and a consequential and incentive compatible payment mechanism (Arrow et al., 1993; Kling, Phaneuf and Zhao, 2012; Haab et al., 2013). The design of the contingent valuation studies for Hverahlíð and Eldvörp has borne in mind all of the best practice guidelines discussed in these works (particularly the NOAA panel report by Arrow et al., 1993) and, as such, will represent a best practice approach for any future Icelandic study to follow.

Although contingent valuation studies typically rely on hypothetical scenarios, they need to remain as real as possible, (Cummings and Taylor, 1998). As Hverahlíð and Eldvörp are two of the fourteen geothermal projects classified by the Master Plan as 'suitable for development', it is conceivable that power plants will be developed at these sites in the future. Moreover, both areas have already been subject to Environmental Impact Assessments on the basis of provisional designs for power plant projects and associated infrastructure. Survey participants will be provided with a comprehensive description and photographs of the area, and will be informed about the likely environmental impacts deriving from the development of power plant projects. In addition, they will be reminded that there are no legal barriers preventing the development of these geothermal areas. As preservation of the areas via the passing of national legislation would entail forgone future economic benefits, the survey's scenario proposes that an additional lump-sum tax (paid for one year only) would be necessary to ensure their preservation. The payment vehicle was chosen due to its incentive compatibility compared to voluntary arrangements. In its design it is very similar to other lump-sum taxes in Iceland, such as the annual fixed levy paid for state radio and television production. Following the scenario description, participants will reminded about their budget constraint and answer a question concerning whether they were for or against the preservation of Hverahlíð/Eldvörp, much akin to the process in referendum voting (Kling et al., 2012).

The CVM literature is full of different ways of eliciting WTP estimates using contingent valuation studies. Over the past twenty years, the dichotomous choice method has become widely accepted as the most suitable due to its ease of use in data collection (Antony and Rao, 2010) and statistical efficiency compared to many alternative approaches (Hanemann et al., 1991). In these studies, the double bounded version of the dichotomous choice method will be used. This approach adds a second bid offer based on a participant's response to their first bid offer. For all individuals with a WTP for the preservation of Hverahlíð/ Eldvörp, if their answer to the first bid offer is 'no' then the second question will offer a lower amount; if the answer to the first bid offer is 'yes' then a higher amount will be asked (Hanemann et al., 1991). In these studies, the accuracy of the WTP distribution across the sample will be enhanced by randomly varying the bid amounts, in so doing reducing the possible influence of starting-point bias (Veronesi et al., 2011). Statistical modelling of the results will be undertaken using interval regression, a more general version of the Tobit model (Cameron and Huppert, 1989; Caudill and Long, 2010; Lu and Shon, 2012).

These studies will also follow an emerging trend in recent years for large-scale contingent valuation surveys to be conducted using the internet (Lindhjem and Navrud, 2011; Bonnichsen and Olsen, 2016). This approach has particular advantages in terms of securing a large and representative sample of the Icelandic population, provides participants with as much they need to complete the survey (unlike interview approaches), and offers the flexibility necessary to randomly vary the bid amounts.

5. Conclusion and policy implications

The OECD has repeatedly called for the Iceland to expand the role of economic analysis within cost-benefit assessments, especially related to the environmental impacts of future energy projects. Despite a policy agenda which encourages the sustainable utilisation of Iceland's renewable energy resources, the enshrining in law in 2013 of a strategic Master Plan for Hydro and Geothermal Energy Resources and a requirement since 1994 for all energy projects to carry out Environmental Impact Assessments, decision-making concerning future energy projects in Iceland remains prone, potentially at least, to a layer of discretion. Failure to value economically the environmental impacts of energy project proposals leads to the monetary gains of projects being compared against the entirely qualitative nature of their environmental impacts. This is an act of non-standardisation that potentially renders the latter insufficiently represented and the overall social welfare implications of project approvals left undetermined. The risks of distorted outcomes from cost-benefit assessments are further exacerbated when developers are in charge of the calculation process.

Key lessons can be learned from the US approach in terms of advancing the practice of conducting cost-benefit assessments for Icelandic energy projects. The imposition of legislation requiring in independent preparation and submission of a cost benefit assessment to decision-makers is of paramount importance to enforce the practice in Iceland. A legislative and policy context in which there is a standardised system for appraising the total costs and benefits of proposals would greatly limit the flexibility of decision-makers to make a decision averse to the public interest. In order to ensure that the principles of transparency and standardisation are embedded within any future process, a set of guidelines would need to be established. Skipulagsstofnun could administer and ensure the implementation of this guidance, which could be based on an adapted version of the US' 'Guidelines for Preparing Economic Analysis'. Orkustofnun would retain sole responsibility for awarding licenses, but would not be permitted to undertake projects that failed the benefit-cost test.

Utilising the total economic valuation framework delineated in this paper can be a very effective means of identifying the specific ecosystem services providing environmental benefits to society, and then the most appropriate non-market valuation technique to estimate the economic value of these. The upcoming contingent valuation studies on the geothermal areas of Hverahlíð and Eldvörp serve as an illustration of a carefully conceived methodology that could be applied to a future Icelandic energy project. Many of these are set to occur in remote areas where a significant proportion of their total economic value may derive from non-use value. In all cases, however, it is necessary for project-specific consideration to be given to identifying the most suitable non-market valuation technique(s) for estimating the environmental benefits set to be sacrificed.

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4. Paper III: An ecosystem services perspective for classifying and valuing the environmental impacts of geothermal power projects

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An ecosystem services perspective for classifying and valuing the environmental impacts of geothermal power projects

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ABSTRACT

An ecosystem services perspective can provide a useful means of understanding, in human well-being terms, the type, scale and value of environmental impacts deriving from the deployment of renewable energy technologies. This paper provides the first thematic review of the ecosystem service impacts commonly associated with developing geothermal areas for power projects. In this study, the typical ecosystem service impacts of geothermal power projects are classified using the Common International Classification of Ecosystem Services (CICES) typology. Next, in order to develop a guide for future practitioners, an analysis is conducted of the most suitable valuation methods for the respective ecosystem service impacts. A pluralist approach is advised to aide decision-making, involving the use of monetary and non-monetary information. A number of non-market valuation studies may be required to estimate the total economic value of affected geothermal ecosystems, likely including the contingent valuation and travel cost methods. The more intangible ecosystem services associated with geothermal areas, such as artistic inspiration and landscape aesthetics, are best valued using non-monetary approaches, including deliberative methods. Finally, in recognition of the importance of having a strong physical basis underpinning non-market valuation techniques, this paper critically assesses the merits of the most appropriate data sources for future environmental economists working in a geothermal context. A literature review reveals that neither Environmental Impact Assessments (EIA) nor Life Cycle Analysis (LCA) studies in a geothermal context have embedded an ecosystem service perspective into their processes. EIA are closest to fulfilling the needs of environmental economists, encompassing the majority of ecosystem service impacts, yet further methodological progress is recommended to ensure that all project stakeholders are given voice and arbitrage in the data-gathering process.

Introduction

Renewable energy transition and increasing significance of geothermal energy

Growing global energy demand and sustainable energy development

The use of energy is essential to the maintenance and advancement of human well-being, ensuring the functionality of economic activities, governments, hospitals and emergency services, public transport, agricultural systems and communication networks. It is expected that population growth and economic expansion could lead to growth in global energy demand of 37% by 2040 (IEA, 2014). In meeting such demand, continued reliance on the use of fossil fuels would lead to the exacerbation of many environmental problems that already undermine human well-being, including greenhouse gas emissions and climate change impacts, air and water pollution, acid rain, and the destruction of forest ecosystems.

The energy sector can play a crucial role in mitigating global climate change, principally by fulfilling a transition from the use of carbon-intensive fossil fuels to the greater deployment of renewable energy alternatives. The European Union's target for 27% of member state energy generation to be from renewable sources by 2030 reflects the importance of sustainable energy development, a concept involving “the provision of adequate energy services at affordable cost in a secure and environmentally benign manner, in conformity with social and economic development needs” (IAEA/IEA, 2001). Implicit in this definition is recognition that sustainable energy development, as an objective, is tied to the pursuit of human well-being, since its delivery must satisfy socio-economic needs whilst avoiding environmental harms. However, the deployment of renewable energy technologies frequently leads to environmental and social impacts with negative consequences for human well-being. Biomass use in some countries has led to

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desertification, biodiversity loss, and diminished areas of arable land (Hastik et al., 2015). The erection of wind turbines has sometimes presented blights to scenic amenity (Leung and Yang, 2012). When considering the merits of new renewable energy projects, decision-makers frequently have to consider complex trade-offs which weigh the meeting of socio-economic needs against the virtues of nature preservation.

Geothermal energy development

Utilisation of geothermal energy dates back to Palaeolithic times, when hot springs were first used for bathing. In more recent times, geothermal energy has been used widely for electricity generation, as well as direct uses such as in district heating, space heating, industrial and agricultural processes, swimming pools, and spas. Worldwide, a total of 12.6 gigawatts (GW) of geothermal power capacity had been installed by 2014 (BP, 2015). The United States has the largest installed capacity (3.5 GW, 28% of world total), followed by the Philippines (1.9 GW, 15%), Indonesia (1.4 GW, 11%) and New Zealand (1.0 GW, 8%) (BP, 2015). Although as a share of global power generation, geothermal energy represents just 0.3%, it grew in scale by 6.4% in 2014 and provides a significant proportion of total electricity generation in certain countries, such as Kenya (32%), Iceland (30%), El Salvador (25%), and New Zealand (17%) (BP, 2015). Furthermore, the Intergovernmental Panel on Climate Change estimates that geothermal energy could satisfy 5% of global heating demand by 2050 (IPCC, 2012).

Usually considered to be a renewable energy source, the development of geothermal power is nevertheless associated with significant and multi-dimensional sustainability implications. Shortall et al. (2015a) carried out a thematic review of the most important sustainability issues of concern in relation to geothermal power projects, listing multiple environmental and social effects, including air and water quality impacts, noise emissions, soil erosion and land degradation, deforestation, loss of biodiversity and impacts to recreational and cultural amenity. As geothermal power is expected to grow in significance in the coming decades, particularly hydrothermal fields harnessed for electricity generation, it is important that these energy resources are utilised in a sustainable manner, with due consideration given to all well-being impacts related to their development.

Analysing the environmental impacts of renewable energy technologies – the ecosystem services perspective

Ecosystem services are the functions of the environment that support, either directly or indirectly, human well-being (Costanza et al., 1997; Daily, 1997; MEA, 2005; Haines-Young and Potschin, 2010). Understanding the links between the processes and functionality of ecosystems and their ultimate contribution to human well-being is of critical importance to a wide-range of decision-making contexts (De Groot et al., 2002; Wallace, 2007; Fisher et al., 2009). Due to the public goods characteristics of ecosystem services, they are typically not assigned their full value in land-use decision-making (Loomis et al., 2000; Boyd and Banzhaf, 2007; Fisher et al., 2009; Simpson, 2014).

A recent study by Hastik et al. (2015) used the CICES framework to provide a detailed thematic review of the ecosystem service impacts associated with biomass production, hydro power, wind power, and solar photovoltaics. The paper considerably advanced the literature base with regards to identifying and comparing the potential ecosystem services impacts and land management trade-offs associated with harnessing these renewable energy technologies. However, although the authors briefly discussed the impacts of geothermal power, this paper's first aim is to provide a detailed thematic classification of ecosystem service impacts in a geothermal energy context. Such a study is long overdue in view of the distinct land-management complexities associated with harnessing such resources (Thayer, 1981; Shortall et al., 2015a). Not only are geothermal areas unique in terms of their geophysical, geomorphological and biological characteristics, all stages of the fuel cycle are located at the production site, increasing the likelihood that a multitude of ecosystem services may have to be sacrificed, both during the construction phase and subsequent operation of plant infrastructure and transmission lines.

Valuing ecosystem services impacts

The debate concerning the use of monetary or non-monetary sources of information to value ecosystem service impacts has been heated in recent years, and includes three disparate schools of thought. On the one hand, arguments have abounded for the use of monetary valuation on the grounds that this approach leads to the increased likelihood of protecting highly valued resources, both through knowledge accumulation concerning the economic value of their sacrifice and integration into cost-benefit analysis (Myers, 1997; Atkinson and Mourato, 2008; Koundouri et al., 2009; De Groot et al., 2010; Dixon et al., 2013). On the other, critics have asserted that economic valuations of ecosystem service impacts lead neither to the conservation of resources (Heal, 2000; Simpson, 2014) nor constitute a necessary or sufficient means for decision-makers to make coherent and consistent choices about the environment (Vatn and Bromley, 1994). The third view – adopted in this paper – is more pluralist, maintaining that coherence in cost-benefit analysis can be maintained through the use of monetary data, provided that appropriate complementary, non-monetary sources of information are also used in decision-making processes (Fisher et al., 2009; Wegner and Pascual, 2011).

To date, only one study has attempted to estimate the economic value of preserving a geothermal area intact, the contingent valuation assessment by Thayer (1981). Given the absence of valuation studies in a geothermal context, a second aim of this paper is to extend the thematic classification of ecosystem service impacts relating to geothermal power projects, applying a set of general criteria to determine whether monetary or non-monetary information is best suited for the valuation of respective ecosystem service impacts. Where monetary information is deemed appropriate, the paper outlines the most appropriate non-market economic valuation techniques to be used in future valuation studies. In so doing, a methodological guide is developed as a form of practical starting-point for future valuation studies.

Assessing impacts to ecosystem service impacts

A strong physical basis is critical to the success of non-market valuation techniques and their ultimate usefulness in decision-making (Cook et al., 2016). In a geothermal context, no studies have sought to evaluate the optimal approach for identifying, in a scientific manner, the degree of qualitative change to ecosystem services, with a view to communicating such information in non-market valuation techniques. Therefore, this paper's third aim is to discuss the two main techniques – LCA and EIA – that could be used to qualitatively assess the ecosystem service impacts of developing hydrothermal fields. All reviewed studies are recent assessments specific to the context of geothermal power.

Paper structure

The organization of this article is as follows. The Ecosystem service impacts and classification frameworks for geothermal power projects section begins by providing an overview of the ecosystem services concept, broad environmental characteristics of undeveloped hydrothermal fields, and classifies the ecosystem service impacts typically associated with their development. The Valuing ecosystem service impacts from geothermal power projects section constructs a framework for valuing these impacts, discussing the various monetary and non-monetary techniques available, and then evaluating their applicability specific to a geothermal energy context. The Discussion section discusses (a) the respective advantages and disadvantages of relying on either LCA or EIA for practitioners seeking to fathom the change in provisioned quantity and/or quality of ecosystem services in a geothermal context, (b) some of the practical challenges in conducting non-market valuation techniques in this context, and (c) the limits of the ecosystem services perspective in terms of evaluating the sustainability of a geothermal power project.

Ecosystem service impacts and classification frameworks for geothermal power projects

Ecosystem services research

Over the past two decades, there has been a growing appetite and burgeoning volume of research into providing an ecosystem services framework to conservation policy, culminating in the production of the Millennium Ecosystem Assessment, a highly popularised body of work formed from the input of over 1300 scientists (MEA, 2005). Perhaps the most widely discussed outcome from the MEA was the finding that globally 15 of the 24 ecosystem services studied were in decline. Given their link to human well-being, such decline is problematic, and should act as a springboard for further research into assessing changes in their provisioning. Fisher et al. (2009) contend that the scientific community needs to (a) communicate clearly what ecosystem services are, and (b) appropriately classify them for use in valuation. The fulfilment of part (a) demands a clear but functional definition and understanding of the ecological characteristics that will be incorporated within a preferred classification scheme. Equally, an appropriate classification of ecosystem services demands an initial understanding of the particular ecological context and typical phenomena that characterise a study location (MEA, 2005; Kumar, 2010).

Definition of ecosystem services

A universally accepted definition does not exist in the academic literature, but several similar perspectives have been conveyed, all of which recognise that ecosystem services relate to human well-being benefits sourced from ecological phenomena. For the purposes of this paper, the broad yet operational definition set out by Fisher et al. (2009) shall be used. Their two key points are that ecosystem services are ecological phenomena arising from biotic and abiotic processes and they do not have to be directly consumed – in other words, the definition recognises that services received indirectly, such as those sourced from carbon sequestration or water purification, contribute to human well-being.

Characteristics of geothermal regions

The features of undeveloped hydrothermal fields vary considerably, but include a) thermal energy stored in rocks deep in the earth and conveyed by water, and b) mineral fluids (for example, calcites, sulphates, silica, lithium, quartz and heavy metals) (Dickie and Luketina, 2005). The characteristics associated with these two features manifest themselves at surface level in terms of various geophysical, geomorphological and biological features. They commonly include:

- Surface discharges of steam, gases, water and other minerals;
- Depositions of minerals, such as silica, that promote the process of mineral cycling and are often useful ingredients in skin products;
- Time dependent behaviour such as geysers, fumaroles, mud flows and hydrothermal eruptions;
- Heated or chemically altered ground surfaces;
- Emissions of hydrogen sulphide, methane, ammonia and carbon dioxide, along with trace elements such as mercury and arsenic;
- Geo-diverse environments including land formations and old geomorphological features deriving from geothermal processes, such as eruption craters, sinter terraces and caves;
- Terrestrial and aquatic ecosystems developed via complex interactions between heat, fluid chemistry, and gases, which lead to often biodiverse environments possessing unique or rare forms of flora (mosses, flora, ferns and fungi), fauna (especially migratory bird species), genetic materials (enzymes often used as amplifiers of DNA fragments in forensics), algae (used in biomass and biofuels production), bacteria (used in industrial applications for biodegradation) and various microbes (help to slow water flows and acting as waste management agents by reducing concentrations of toxins and heavy metals that disperse to the wider environment).

Where geothermal regions containing some or all of these characteristics are publically accessible, they often become attractive for various recreational activities, such as bathing in hot springs or simply the enjoyment of visiting a rare, dynamic and evolving landscape (Dowling, 2013; Borović and Marković, 2015; Liu and Chen, 2015). Equally, these environments can be a source of inspiration for artists due to their diverse aesthetical qualities (Gray, 2012). Spiritual beliefs and practices can relate to geothermal regions, such as those held by the Maori culture in New Zealand (Zeppel, 1997; Shortall et al., 2015a), while indigenous groups may hold notions of the sacred value of land connected to features of symbolic importance (Lund, 2006). In addition, although geothermal areas are generally sparsely populated, they can sometimes possess important archaeological remains (Borović and Marković, 2015).

Ecosystem services impacted through the development of geothermal power projects

Building on the summary of characteristics common to geothermal areas, a general inventory of ecosystem service impacts was formed, based on the typical changes relating to the development of a hydrothermal field.[1] Given the general thematic context of this paper's analysis, the inventory is not exhaustive and nor will every ecosystem service impact be applicable to an actual project setting. However, to summarise very briefly, it is common for the development of a geothermal power plant and its associated infrastructure – drilling wells, pipelines, transmission lines etc. – to result in a reduction in the quantity or quality of some or all of the following ecosystem services: freshwater provision; biodiversity; geo-diversity; mineral deposition, water and waste purification rates; air and water quality regulation, archaeological heritage; recreational amenity; artistic inspiration; aesthetics; spiritual enrichment; and other cultural associations related to existence, altruistic and bequest values.

The construction and operation of a geothermal power plant has the potential to present risks to human well-being. Although evidence suggests no harm to human health following long-term exposure to ambient concentrations (Bates et al., 2015), hydrogen sulphide emissions can hike considerably during the operation of a power plant, potentially to concentrations that have been proven to be harmful to human health in the form of eye irritation and breathing difficulties (Ermak et al., 1980), as well as impacting negatively on local biodiversity (Brophy, 1997; Phillips, 2010). Other pollutants occurring during a plant's construction or operation may involve the release of acidic/alkaline effluent into local watercourses, or effluent including chlorides, sulphides, or dissolved toxic chemicals (Shortall et al., 2015a). In addition, heavy metal water pollution from geothermal power plants has been documented, with production at the Wairakei Power Plant in New Zealand leading to arsenic levels in the Waikato River to more than double and exceed drinking water standards (Ray, 2001). Where geothermal

[1] For the purposes of this analysis, the deep sub-surface manifestations of geothermal energy were not considered to be an ecosystem service, as they do not provide a direct or indirect source of human well-being deriving from the product of an ecosystem. However, their surface expressions, such as the interaction of heat, fluids and minerals to provide suitable bathing facilities for tourists, are encompassed within such an ecosystem services perspective.

developments take place in water scarce regions, there is the potential for power projects to conflict with the freshwater demands of the local population – freshwater supplies are required during drilling, construction and operation of a power plant (Shortall et al., 2015a).

At the project-specific level, the construction of geothermal power plants may have the potential to cause habitat loss and degradation for a variety of flora and fauna due to waste emissions, over-abstraction of water from reservoirs, noise and thermal disturbances. For example, the development of the Olkaria Geothermal Field in Hell's Gate National Park, Kenya necessitated the locating of transmission lines to avoid crossing Hell's Gate Gorge and the Fischer's and Central Towers, important breeding and nesting grounds for several migratory species (Mwangi, 2006).

With regards to recreational amenity, it is likely that this will diminish due to the development of a geothermal power project, often due to an undermining of the sense of peace caused by visual blight and noise emissions occurring during drilling, construction and operation (Brophy, 1997). However, there are examples where geothermal power plants have increased recreational amenity in certain areas, as Iceland's Blue Lagoon spa testifies. Formed in 1976 from the waste waters of the Svartsengi Power Plant, the geothermal spa has continued to attract a growing band of tourists keen to relax in its therapeutic lagoon (Blue Lagoon, 2015). In addition, the Hellisheiði Geothermal Plant, located around 30 km to the east of Reykjavik, has constructed a popular interactive exhibition for tourists (ON Power, 2016).

In some cases, human well-being impacts caused by geothermal power projects may also be experienced by individuals living well outside the geographical locality of the developed area, generally due to cultural associations. Individuals who value a particular geothermal landscape, but have never benefited from the provisioning of its ecosystem services, may wish to retain an option to do so in the future. Others may have no intention to frequent the area and instead simply value the intrinsic qualities of its rare environment and ecosystems.

Classifying the ecosystem service impacts of geothermal power projects

In order to advance the inventory of ecosystem services so as to formulate a coherent framework for undertaking land management decisions, these must now be classified in a manner sufficient for trade-offs to be considered and valuations of impacts – monetary and/or non-monetary – to take place. For this purpose, this paper accords with the approach taken by Hastik et al. (2015) and adopts the CICES typology (2013). CICES was formed in 2013 out of recognition that various other classification frameworks, such as those developed within the MEA and The Economics of Ecosystems and Biodiversity (TEEB), were based on different methodological underpinnings, and there was a need for a simplified and standardised approach (Haines-Young and Potschin, 2010; Saastamoinen, 2014). CICES relies on three categories of outputs relating to provisioning, regulating and cultural ecosystem services.

Table 1
Classification of ecosystem service impacts to geothermal areas.

CICES category	Ecosystem service impacted
Provisioning	Genetic resources
	Freshwater supplies
	Mineral resources
Regulating	Water purification
	Waste treatment
	Air quality regulation
Cultural	Recreational amenity
	Spiritual enrichment
	Aesthetics
	Inspiration
	Archaeological heritage
	Other cultural associations

Table 1 classifies the inventory of likely ecosystem service impacts deriving from geothermal power projects according to the CICES typology. In all cases the impacts are assumed to be negative, however, as already stated, this is not necessarily the case in a project-specific scenario. Table 1 avoids direct references to biodiversity, as this is deemed to be a multi-attribute state of complexity and variety of wildlife supporting final human well-being benefits in the form of provisioning and various cultural ecosystem services (Nunes and van den Bergh, 2001; De Groot et al., 2010; Mace et al., 2012). Recognising biodiversity in its own right, rather than a contributing process, would inevitably lead to an unnecessary duplication of well-being benefits.

Valuing ecosystem service impacts from geothermal power projects

Measuring impacts to ecosystem services

Economic valuation and non-market valuation methods

Valuing ecosystem services and their impacts using monetary information relies on a utilitarian (anthropocentric) interpretation of value, as opposed to a non-utilitarian perspective grounded in ethical, cultural and philosophical bases. As the introduction to this paper set out, often ideological reasoning among practitioners leads to a choice between valuing ecosystem service impacts using monetary or non-monetary information. Despite the limitations of applying economic valuation techniques to value impacts to all ecosystem services (Vatn and Bromley, 1994; Spash and Hanley, 1995; Primmer and Furman, 2012), their use remains legitimate and important where human interventions are set to influence the characteristics of environmental resources.

Presenting environmental and sustainability implications purely in terms of their physical consequences – as per an Environmental Impact Assessment – presents even more difficult challenges for land use decision-making, as the monetary gains of a project are not directly comparable with the qualitative nature of resource degradation or loss. Moreover, as decision-making and policy formation is undertaken by human beings, a money metric reveals human preferences and can appraise the relative value of different development options (Champ et al., 2003; Freeman, 2003; Fisher et al., 2009; Dixon et al., 2013).

The most commonly applied framework for organising the economic value of ecosystem service impacts is the concept of Total Economic Value (TEV). As Fig. 1 portrays and Table 2 further explains, economists have typically split the total economic value of natural resources into two main components: use and non-use value (Tietenberg, 1988; Davíðsdóttir, 2010; Hanley et al., 2013). Non-use value is derived purely from the knowledge that a resource is preserved intact for the future (Krutilla, 1967; Hanley et al., 2013).

Several market and non-market economic techniques exist to estimate use and non-use sources of value, and these are generally split according to whether they are revealed or stated preference methods. Table 3 summarises the characteristics of the most common techniques.

Non-monetary valuation methods

There are clearly aspects of human well-being related to cultural ecosystem services that fall outside of the utilitarian perspective and cannot be inferred indirectly from utilitarian measures, such as the value of inspiration or notions of beauty connected to aesthetics. Many academics have criticised the use of economic valuation techniques for valuing these impacts on the grounds that a money metric fails to identify such sources of value (Wilson and Howarth, 2002; Christie et al., 2006). Often an individual's willingness to pay for such services will be zero, yet they are willing to invest more time to ensure the conservation of a particular resource (Higuera et al., 2013). Where cultural ecosystem services relate to non-material benefits (e.g. heritage, aesthetical, moral, spiritual or inspirational connotations) or intangible socio-cultural aspects that exist purely in the minds of individuals, these values are best expressed using non-monetary information. In recent years, deliberative methods and multi-criteria decision analysis

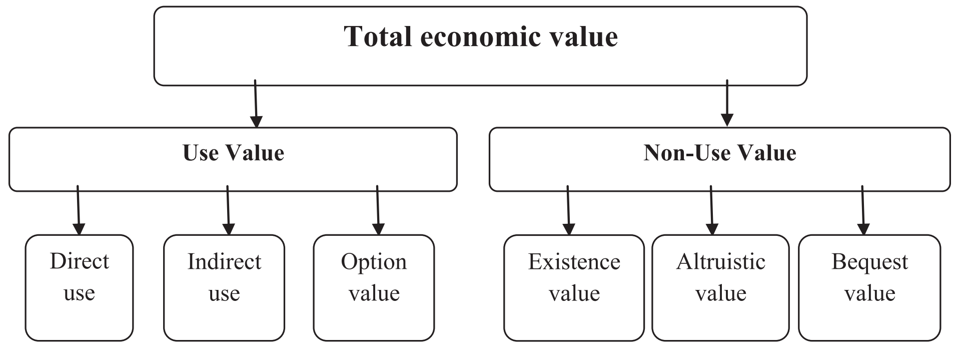

Fig. 1. Total economic value framework.

have become increasingly popular ways of representing such values to inform decision-making processes.

For impacts to the ecosystem services of aesthetics and spiritual enrichment, where ethical arguments abound, various deliberative methods, including citizens' juries and focus groups, may be used to express unquantifiable and intrinsic values via words rather than enumeration (Sagoff, 2004; Chan et al., 2012). Cooper (2009) argues in favour of a process of casuistry to represent spiritual and aesthetical values within the ecosystem services debate – such a moralistic approach is broadly akin to Landsberg et al.'s (2011) call for greater delineation of the beneficiaries of ecosystem services and values held by all participants. Deliberative methods involve the provision of information to groups of citizens concerning the impacts of development initiatives, providing these individuals with the necessary time to reflect, discuss and question the many values and trade-offs, prior to arriving at some sort of consensus (Antunes et al., 2009). The challenge for deliberative methods is to ensure that they are fully inclusive and representative of all value interests (Chan et al., 2012), and unbiased by any form of politically motivated manipulation.

Differences in aesthetical and spiritual values across the demographic and geographic spectrum could be captured using perceptual surveys (Daniel, 2001). Such approaches can assess changes in visual aesthetic quality using relative measures (preference scales) for specified populations, providing an informed basis for further trade-off negotiations in discussion groups and focus groups.

Multi-criteria decision analysis is an increasingly popular tool for reconciling the flaws of cost benefit analysis, where the use of a single money metric is inappropriate for representing the costs of degrading certain ecosystem services, and is thus inadequate on its own for comparing trade-offs. Rather than focusing on purely economic efficiency as an objective (Wegner and Pascual, 2011), multi-criteria decision analysis evaluates projects in terms of multiple objectives, such as economic efficiency, levelised cost, ecological resilience, access to renewable energy, maintaining a certain level of recreational amenity, poverty relief etc. Units of measurement in multi-criteria decision analysis are not necessarily money, but rather each alternative policy option is scored and weighted according to the importance of each objective, with an average score formed for each policy alternative. Haralambopoulos and Polatidis (2003) employed the PROMETHEE II multi-criteria decision analysis tool to support group decision-making concerning the development of a new geothermal technology in Chios, Greece. Five criteria were taken into account: conventional energy saved (tonnes of oil per year), return of investment (yearly earnings per initial investment), number of jobs created, environmental pressures, and entrepreneurial risk of investment (Taha and Daim, 2013).

Critics of multi-criteria decision analysis have contended that the approach is liable to subjectivity in terms of its weighting and aggregation procedure, while significant power asymmetries may remain among participating stakeholders (Vatn, 2005).

Valuing ecosystem service impacts – choosing monetary or non-monetary information

Fisher et al. (2009) state that following the identification of impacts in an ecosystem services classification, it is up to the users of the framework to then determine the specific cases where economic valuation techniques are appropriate. This approach reflects the concept of value pluralism, recognising that any valuation of the environment demands the use of multiple 'valuation languages', whereby values may be combined to inform decisions and may even overlap to a degree, but cannot be reduced to a single metric (Gómez-Baggethun and Barton, 2013).

Where the goal of the decision-context is to apply economic valuation techniques to cost-benefit analysis, with the aim of forming a more complete estimate of the true welfare gains/losses of a project, there is a need to form coherent links between the chosen classification framework for ecosystem services, impacts to ecosystem services from

Table 2
Components of the total economic value framework.

Use value	Explanation
Direct use	The services that human beings directly benefit from following a planned demand. This may take the form of consumptive use (e.g. provisioning services such as food) or non-consumptive involving no drawing down of resource stocks (e.g. receipt of spiritual, inspirational, aesthetical and recreational benefits). Consumptive forms of direct use value can generally be expressed via market transactions, while non-consumptive cannot.
Indirect use	Indirect use values are a form of vicarious consumption broadly relating to regulating and supporting ecosystem services. Although critical to the survival of life on the planet, these are typically ignored in economic valuations (Mitchell and Carson, 1989). Either an individual does not receive direct benefits or their monetisation would lead to double counting.
Option value	Option values relate to the retention of the possibility to gain benefits from using a resource in the future, either directly or indirectly (Weisbrod, 1964; Hanemann, 1989).
Non-use value	
Existence	Existence values describes the increases in well-being individuals obtain from simply knowing that a resource exists, despite no intention to demand its ecosystem services, now or in the future.
Altruistic	The benefits gained from knowing that others can benefit from a preserved resource, either now or in the future.
Bequest	The benefits gained from knowing that future generations will be able to benefit from a preserved resource.

Table 3
Revealed and stated preference valuation techniques.

Revealed preference	Explanation of technique
Market pricing	The monetary value of provisioning services (e.g. food, fibre, genetic resources) sold in the marketplace is used to reflect the value of commodities.
Avoided cost (also known as damage cost avoided)	Avoided cost techniques appraise expenses incurred by individuals in response to negative change in the quality of an environment, for example buying bottled water to avoid the risk of consuming polluted freshwater supplies.
Replacement cost	The replacement cost technique uses the cost of replacing an ecosystem service as an estimate of its value. This requires that perfect substitutes for an ecosystem service are available.
Production function approaches	Production function approaches estimate how much an ecosystem service contributes to the provisioning of a tradable ecosystem service (Pattanayak and Kramer, 2001), which is then valued via the market value of its enhancement contribution to income or productivity.
Hedonic pricing	Hedonic pricing is a technique used to estimate economic values for environmental services that directly influence the market prices of goods (Tyrväinen, 1997). For instance, the market value of houses is influenced by a number of variables, some of which may be environmental in nature, such as proximity to recreational areas. The approach involves three key steps: (1) estimation of the hedonic price function describing the unit price of a commodity as a function of its vector of characteristics (including ecosystem service component of interest); (2) calculation of implicit characteristic prices as the derivative of the hedonic price function; and (3) estimation of the demand curve for the chosen ecosystem service.
Travel cost method	The travel cost method relies on the cost of travelling to a location and the opportunity cost of time as a proxy for the recreational benefits provided by a resource (Mitchell and Carson, 1989; Driml, 2002; Fleming and Cook, 2008), assuming that the costs of visiting a place increase as distance increases (Hotelling, 1947). Once this information has been obtained, a demand function can be formed, so as to estimate the economic value of recreational benefits.
Stated preference	
Contingent valuation method	This technique is labeled 'contingent' as it relies on a scenario, typically hypothetical, to estimate the value that a person places on an environmental good. The scenario describes the institutional context in which the good will be provided and the way it will be financed (Mitchell and Carson, 1989; Carson, 2012). Surveys often aim to elicit individuals' willingness to pay (WTP) to preserve an ecosystem service or examine WTP for an improvement in environmental quality, for example WTP for increased liming to reduce acidification and stimulate increased freshwater fish stocks. Using the CVM, the environmental costs or benefits of a particular development project can be estimated and aggregated in terms of their individual effects on ecosystem services (great care is needed to ensure double counting does not take place) or stand-alone evaluations of the overall impacts can be conducted. Unlike revealed preference methods, which only estimate use value, the CVM can also be used to estimate non-use value.
Choice modelling	Choice modelling is similar to the contingent valuation method in terms of its theoretical foundations and capacity to estimate use and non-use value. In contrast, however, it presents participants with at least two possibilities concerning the future environmental attributes of an area. Survey participants are requested to rate, rank, or select their most preferred alternative, and by including price or cost as one of the bundle of attributes, WTP can be indirectly estimated from the choices made.

project-specific proposals, components of the total economic valuation framework, and the most suitable non-market valuation method. Rather than applying arbitrary judgment calls concerning whether to use monetary or non-monetary information, three general criteria were applied to inform the decision-making process:

1) Scientific validity – particularly in the case of provisioning resources, can the scientific relationship be determined between the input of a provisioning service and its contribution to the output price and quantity of a good demanded?
2) Reliability – does a non-market economic valuation technique exist that could theoretically be applied to value this ecosystem service impact in this context?
3) Value commensurability – does the impact to the ecosystem service relate to a utilitarian or non-utilitarian notion of value?

Table 4 reflects on these criteria to set out for the ecosystem service impacts that should ideally, from a theoretical perspective, be valued using monetary information, the links between ecosystem service impacts, economic valuation methods, and components of the TEV.

For each ecosystem service, the analysis in Table 4 provides a reasoned justification concerning whether monetary information should generally be utilised. Links are identified between ecosystem service impacts, non-market valuation methods, and components of the TEV. As this analysis is of the general and thematic type, in a project-specific scenario, practitioners must carefully review and classify the ecosystem service impacts, assess the degree of impact, and determine the feasibility of carrying out sometimes multiple non-market valuation techniques.

Discussion

Sourcing and linking impact data to economic valuations of ecosystem services

Environmental economists conducting economic valuations of ecosystem service impacts are typically ill-equipped to appraise the degree of environmental change or degradation. Rather, they must (or should) rely on interdisciplinary input from environmental experts. In the context of geothermal energy, environmental impacts are typically reported within either Environmental Impact Assessments (EIA) or – slightly less comprehensively in existing studies – Life Cycle Analysis (LCA). EIA requires the identification and prediction of impacts on the environment and human well-being related to legislative proposals, policies, programmes, projects and operational procedures (Munn, 1979). LCA is an advanced technique for assessing the environmental (and increasingly social and socio-economic) impacts of various inputs and outputs of production from a cradle to grave perspective, including, in the case of geothermal energy, the period from raw material extraction at the exploration stage all the way through to the eventual decommissioning and potential recycling of facilities (Baumann, 1998; Sala et al., 2013). Given its already comprehensive scope, it has been argued that LCA should also seek to encompass impacts to ecosystem services (Brandão and i Canals, 2013).

Bearing in mind the importance of embedding economic valuations of ecosystem service impacts within the pool of information provided to decision-makers, in the context of geothermal energy LCA and EIA are reviewed with regards to (a) their current tendency to communicate the likely degree of impact linked to the UK NEA's three categories of services: provisioning, regulating and cultural; and (b) their future potential for fulfilling objective (a) based on recent methodological advances.

Table 4
Ecosystem service impacts of geothermal areas – valuation using monetary or non-monetary information.

CICES classification of ecosystem service impact	Value impacts economically?	Suitable non-market valuation method(s)	Component of the total economic value framework	Justification for utilising/not utilising non-market valuation methods
Provisioning				
Genetic resources - reduction in DNA amplification, biofuels production, and industrial biodegradation	Yes	Production function	Use (direct)	Production functions are capable of indicating the magnitude of production losses in forensic amplification, industrial biodegradation and biomass fuel generation. The relationships between genetic resource inputs to eventual production outputs could be determined via experiments. From this relationship, the marginal product and the change in productive output induced by decreases in the quantity of genetic resources can be determined.
Drinking water – shortage of water for domestic and agricultural use	Yes	Market pricing, avoided cost, replacement cost or production function	Use (direct)	Market pricing could be used to estimate any lost availability of drinking water. Avoided or replacement cost could be used if domestic residents are forced to buy bottled sources of water to replace freshwater supplies. In agriculture, an appropriate approach would be to form water-crop or meat production functions, thus modelling the relationship between water inputs and agricultural production. As per the case of genetic resources, from the calculation of marginal product, the change in agricultural output caused by reductions in the supply of water inputs would need to be determined.
Mineral resources – reduction in production of skin and bathing products	Yes	Production function	Use (direct)	As per text above for the ecosystem service of 'genetic resources'.
Regulating				
Water purification and waste treatment – reduction in water quality and treatment rates necessitating pollution control measures	Yes	Replacement cost or avoided cost	Use (indirect)	There are no existing studies charting the extent to which undeveloped geothermal regions cleanse surrounding watercourses, lakes and reservoirs of toxins and heavy metals. However, where economic valuation studies have been used to estimate this ecosystem service in contexts other than geothermal regions, the replacement cost method has been used, with reference to the costs of operating a water treatment plant to provide the same service (Krieger, 2001). Also, the avoided cost method could be applied if the water purification service was necessary to ensure the provisioning of safe drinking water, and individuals buy bottled sources instead.
Air quality regulation – reduction in clean air and potential decline in the quality of human health	Yes	Avoided cost	Use (indirect)	There is some evidence to suggest that exposure to severe concentrations of hydrogen sulphide emissions will result in chronic health effects (Durand and Wilson, 2006; Bates et al., 2015). One economic approach to valuing health impacts would be to ascertain the aggregate market price of all medical treatment costs relating to the condition. However, this approach is valid only if clear causality is determined linking individual exposure and the health condition. A more practical alternative is likely to be to use the market costs to the developer of installing scrubber technology to ensure that concentration of emissions do not exceed the World Health Organization's safe standards. Similarly, where geothermal plants emit other toxic substances such as mercury, the market costs of installing filter technology can be used as a proxy for the human well-being costs of reduced air quality.
Cultural				
Recreational amenity – negative impacts to recreational amenity, caused principally by visual and noise impacts through the construction of drilling wells, pipelines, transmission lines, plant infrastructure, and potential loss of valued landscape, biodiversity and clean air features	Yes	Travel cost method	Use (indirect)	The travel cost method can be used to estimate the recreational impact of changes to a geothermal resource through a combination of traditional seasonal demand models – demand for use of a site over an entire season – and stated preference data (Parsons, 2013). A comparison of consumer surplus equates to the economic value of impacts to recreational amenity. This approach would also be able to capture instances where the recreational value of geothermal regions happened to increase due to the construction of power plant facilities.
Spiritual enrichment – diminishment or total loss of	No	N/A	Use (indirect)	Where spiritual enrichment is obtained through

Table 4 (*continued*)

CICES classification of ecosystem service impact	Value impacts economically?	Suitable non-market valuation method(s)	Component of the total economic value framework	Justification for utilising/not utilising non-market valuation methods
spiritual significance associated with an area.				undertaking recreational visits to a site, the travel cost model will estimate the economic value of impacts to this service. However, more commonly sites will be of significance to traditional societies, and often such areas are considered to be sacred and beyond economic valuation (Cooper, 2009). Efforts to use stated preference data to translate intrinsic spiritual values into monetary data are hugely controversial and would most probably lead to a large number of protest responses or extraordinarily high elicitations of willingness to pay.
Aesthetics – reduction in the quality of the aesthetical experience experienced in the immediate locality and sometimes beyond in the case of transmission and pipeline impacts	No	N/A	Use (indirect) and non-use	As per spiritual enrichment and inspiration, the value of aesthetics and beauty experienced at a location is captured to some extent within the recreational amenity service. Beauty is also one of the main instigators of a sense of existence value, and so the use of the contingent valuation to estimate non-use value can encompass these experiences in an indirect manner. Specific attempts to apply economic techniques to value the preservation of natural beauty at a site would be fraught with difficulties, leading either to refusals to answer or extravagant expressions of willingness to pay.
Inspiration – likely decline in inspiration, but responses depend entirely on subjectivity concerning the inspirational qualities of power plants and their infrastructure versus the capacity of undeveloped geothermal regions to instil such feelings	No	N/A	Use (indirect) and non-use	Similarly to spiritual enrichment and aesthetics, inspiration is a highly indefinable experience that is best captured in part through the monetary value of recreational amenity and other cultural outputs.
Heritage – loss or disturbance of archaeological remains	No	N/A	Use (indirect) and non-use	The attraction of historical relics and archaeological remains is integral to the recreational value of a site and, at least in part, non-use sources of value. Thus, the economic impacts of losing or degrading such features can be encompassed in part within the welfare estimates generated by travel cost and contingent valuation studies.
Other cultural outputs related to existence, altruistic and bequest sources of value – reduction in human well-being as these values relate to the preservation of a geothermal area for others to enjoy, now and in the future	Yes	Contingent valuation method	All non-use sources (can be used to estimate all types of use value too)	A contingent valuation study is the most common method of estimating non-use value associated with preserving a site and its methods have been applied to a wide variety of environmental contexts (Champ et al., 2003; Carson, 2012). Typically surveys present participants with a detailed scenario of a development threat at a site and proceeds to elicit willingness to pay for its preservation. Sources of non-use value are very likely to include the intangible ecosystem services that should not be valued economically, such as beauty, aesthetics, inspiration, heritage and the maintenance of biodiversity and gene pool diversity. For geothermal regions, which can be remote and rarely frequented by visitors, it is conceivable that non-use value might represent the most significant component in its total economic value.

Identification of ecosystem services impacts within life cycle analysis

Given their fundamental importance to human well-being, a comprehensive review by Zhang et al. (Y. Zhang et al., 2010; Y.I. Zhang et al., 2010) reported on the extent to which LCA accounts for the role of ecosystem services. The authors found that impacts to provisioning services, such as genetic materials and drinking water, were addressed and reported. However, generally impacts were described in terms of indirect impact indicators such as Abiotic Depletion Potential (direct resource depletion and resource depletion occurring during extraction, processing and transportation of the resource) and Surplus Energy (the additional energy needed in the future to extract lower grade resources e.g. the energy used in re-injecting geothermal fields). Neither of these approaches involves a direct investigation of the quantitative change in provisioning capacity (i.e. in terms of the output of provisioning goods) caused by extracting provisioning resources.

LCA methods utilise characterisation factors to translate a project's environmental impacts into common equivalence units – for example in the case of geothermal energy, carbon dioxide for climate change impacts or sulphur dioxide for acidification effects – which are then aggregated to arrive at the total impact (Frank et al., 2012; Bayer et al., 2013). In terms of ecosystem services, this approach is akin to an indirect consideration of impacts to regulatory services, such as climate regulation. With respect to geothermal power projects, LCA currently has no means of expressing quantitative impacts to water purification and waste treatment. As Bayer et al. (2013) observe in their global review of existing LCA studies of geothermal energy, the technique is currently focused on the environmental impacts of production processes, not the much broader ecosystem services perspective focused on impacts to stakeholder well-being. Even connected to this aspect, only a very few LCA studies have so far quantified the direct and indirect environmental impacts of power plant production, and the potential emissions of toxic substances such as mercury, boron and arsenic have been inadequately addressed (Buonocore et al., 2015).

Despite deficiencies in existing studies thus far connected due to geothermal power projects and the considerable volume of data required to form a comprehensive study, LCA retains considerable potential in terms of its capacity to communicate impacts to regulatory and cultural ecosystem services. Recent advances in LCA theory have begun to focus on the development of a globally applicable land use impact assessment method, with a particularly focus on changes in biodiversity during land transformation and occupation. Koellner et al. (2013) were one of the first set of authors to contend that a set of biodiversity-related indicators could be developed to measure impacts to provisioning and regulating ecosystem services deriving from changes in land occupation and its transformation. In particular, the authors scoped out a generic impact pathway for ecosystem services damage potential, emphasising the need to develop characterisation factors for impacts to a range of services, including freshwater regulation and water purification potential (Koellner et al., 2013). A series of recent workshops have helped to develop an emerging consensus concerning the need for biodiversity-related indicators of ecosystem service impacts in LCA, although it has become recognised that as LCA models have commonly addressed potential impacts in a general context, any interpretation of their results by environmental economists will need to be supplemented with the use of more detailed information that accounts for local specifics (Teixeira et al., 2016). As yet, no detail has emerged concerning the set of indicators that could be applied to help realise this methodological advancement (De Souza et al., 2013; Mueller et al., 2014; Teixeira et al., 2016).

Existing LCA evaluations connected to geothermal power projects have not incorporated any qualitative description of impacts to cultural ecosystem services, especially recreational amenity and ‘other cultural outputs’ relating to non-use sources of economic value (Bayer et al., 2013). In the case of impacts to cultural ecosystem services, these are inevitably highly project-specific and potentially significant in the case of geothermal power projects. Bayer et al. (2013) note that power projects in geothermal regions are prone to causing considerable impacts to land of high social value to tourists and natives alike. However, there remains the potential for cultural ecosystem services to become an embedded component in LCA studies. In recent years the development of social LCA has, separately to traditional, environmentally focused LCA, helped to provide an emerging decision support tool for social and socio-economic impacts related to lifecycles (UNEP, 2009; Wu et al., 2014; McManus and Taylor, 2015). Greater levels of standardisation in social LCA studies have begun to occur since the publication of guidelines by the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology (SETAC). The UNEP/SETAC guidelines discuss type I impact categories, those with specific relevance to stakeholders and their well-being (UNEP, 2009). The recent review by Wu et al. (2014) has reported a broad range of indicators in the social LCA studies based on the UNEP/SETAC guidelines. These are typically rights-based indicators relating to impact categories of workers, consumers, local communities and society – for example, fair salary and working hours, equal opportunities in the workplace, consumer privacy, community engagement, public commitment to sustainability issues, prevention of armed conflicts etc. Although not specifically focused on the concept of ecosystem services, the broad scope of social LCA impact categories and a focus on various underpinnings to human well-being lends itself well to the arena of economic valuation. The gathering of site-specific data through surveys and interviews to fulfill a social LCA study could help practitioners of the contingent valuation method to develop realistic and well-informed scenarios, which would be particularly helpful when attempting to estimate non-use value.

The future of social LCA studies and their role as an increasingly relevant part of a suite of decision-making tools may require the integration of an ecosystem services perspective in order to better understand site-specific impacts to human well-being (Croes and Vermeulen, 2015; Dewulf et al., 2015; McManus and Taylor, 2015). Clearly, to some extent, any move in this direction would involve a transition beyond traditional understandings of the role of an LCA study, examining not only cause and effect chains linked to physical elementary flows, but much deeper analysis of societal interactions between the human, natural and industrial environments. Furthermore, it would necessitate a decidedly ‘bottom-up’ shift in the current perspective in LCA studies. This change would demand the adoption of a similar philosophy to the recent myEcoCost approach to assessing the resource use of products, a new methodology whereby all likely ecological impacts occurring during a product's lifecycle are accounted for and directly communicated to relevant stakeholders (von Geibler et al., 2014).

The integration of social LCA components and a stakeholder focus is essential in order for future LCA studies to be able to provide sufficient, credible, and informative data to environmental economists concerning the qualitative nature of ecosystem service impacts. Furthermore, advances in the extent to which environmental impacts are reported within LCA studies are necessary to fulfill this objective.

Identification of ecosystem service impacts within EIA

The aim of EIA is to identify, predict, evaluate, and mitigate “the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made” (Karjalainen et al., 2013). These aspirations are closely aligned to the aims of ecosystem services analysis – impacts to recreational amenity; noise and air emissions; habitat loss; recreational impacts; loss of provisioning goods etc. are all identified as routine components in any EIA – but the approach currently does not currently focus on stakeholder well-being (Karjalainen et al., 2013). As a result, EIA practitioners run the risk of failing to deliberate and report on the needs of certain stakeholders who are vulnerable to the degradation or loss of ecosystem services, particularly the cultural dimensions (Landsberg et al., 2011; Karjalainen et al., 2013) such as the spiritual enrichment gained by indigenous peoples or inspiration offered to artists by frequenting geothermal regions.

It is evident that ecosystem services research has become an increasingly mainstream aspect within land use decision-making but not yet EIA (De Groot et al., 2010; Chan et al., 2012; Karjalainen et al., 2013). Wilson and Howarth (2002) and Karjalainen et al. (2013) discuss the issue of how to incorporate an ecosystem services perspective in EIA that accounts for all of the various cultural and ecological values of affected groups. Coleby et al. (2012) add that one of the major blocks that has prevented the integration of the ecosystem services perspective into EIA is the need for practitioners to gain enhanced understanding of trade-offs and societal preferences at different spatial and temporal scales. Expanding EIA to include an ecosystem services perspective leads to increased complexity for practitioners in terms of what matters and to whom.

Landsberg et al. (2011) have developed one framework for integrating an ecosystem services perspective into EIA. Their ‘Ecosystems Review for Impact Assessment’ highlights the importance of practitioners delineating interactions between a project, human well-being and the direct and indirect drivers of ecosystem service impacts. The emphasis in their approach is shifted towards an integrated assessment of ecosystem service impacts and societal beneficiaries. Landsberg et al. (2011) argue that it will lead to three benefits: (1) more inclusive stakeholder engagement; (2) more comprehensive assessment of social impacts; and (3) greater likelihood that stakeholders do not lose the well-being benefits they derive from impacted ecosystem services. For instance, with regards to point (3) in a geothermal context, when looking at a reduction in recreational amenity for certain populations due to a power project, Landsberg et al.'s (2011) approach might be effective in stimulating mitigation measures (e.g. locating certain pipes underground) focused on ensuring minimal disturbance to local footpaths, bridleways and the overall landscape. In addition, the approach has the potential to foster more democratic ideals within EIA and decision-making processes. As Gregory et al. (2012) comment, when land-use planning is typified by stakeholder controversy, it is all the more important for decision-makers to understand the benefits received and values held by all the affected participants. In keeping with a call in the UK NEA (2011) for the consideration of 'shared social values', Landsberg et al.'s approach accords well with the philosophy underpinning the Total Economic Valuation framework. Determining whose preferences matter and facilitating the elicitation of these appear to remain the most significant barriers to encompassing an ecosystem services perspective in EIA. Overcoming this shortcoming could involve the use of World Cafe style workshops, a participatory approach that has been successful in the recent development of the Geothermal Sustainability Assessment Protocol (Shortall et al., 2015b).

Challenges of conducting economic valuation techniques for ecosystem service impacts associated with geothermal power projects

Table 4's analysis can be applied using three different approaches to estimating the TEV of preserving a geothermal area: (1) each of the ecosystem service impacts that this paper argues should be valued economically are monetised and then aggregated using the appropriate techniques; (2) the contingent valuation method is used to arrive at a single estimate of the total economic value of preservation, including all use and non-use value components; (3) a combination of revealed and stated preference methods are used to estimate the economic value of impacts to recreational amenity and non-use value respectively, with these values aggregated to arrive at an estimate – almost certainly an underestimate – of the TEV.

The first of these three approaches is optimal from a theoretical perspective but may not always be feasible in an actual project setting, as there are frequently challenges associated with carrying out non-market valuation techniques. Particularly in relation to the ecosystem service impacts that should be valued using the production function approach, considerable time and resources must be dedicated to establish the biophysical links between the provisioning inputs and their contribution to the quantity and quality of the good produced, as well as its eventual price. Thus, the second and third approaches are more likely to be applied in practice.

The second approach was adopted by Thayer (1981) in his PhD project, which included a study of the economic value of preserving the Santa Fe National Forest in New Mexico, a diverse, scenically attractive and popular recreational area blessed with geothermal activity, including surface manifestations such as hot springs. As far as the authors of this paper are aware, Thayer's work remains the only study to date which has attempted to estimate the economic value of preserving a hydrothermal area instead of developing a power plant. Thayer (1981) carefully described the likely environmental impacts of the project when constructing the survey's scenario. Without referencing the term 'ecosystem services', a concept in its absolute infancy in 1981, his descriptions of environmental impacts bore close assimilation to this perspective. Commencing with a portrayal of the irreconcilability between a geothermal power project and sustaining the current level of recreational amenity, the study then communicated to survey participants the three major impacts to recreational amenity deriving from a geothermal power project at Santa Fe National Forest: (a) visual blights relating to the removal of vegetative cover and instigation of drilling, pipelines, transmission lines, and plant facilities; (b) emissions of noxious gases once the power plant was operational, leading to a reduction in air quality; and (c) increased noise emissions reducing peace, quiet and opportunities for solitude (Thayer, 1981).

Thayer's use of the contingent valuation method relies on the fundamental assumption that participants are able to comprehend the provided scenario and have an economic value for preserving the geothermal area in question. The academic literature has tended to focus on potential sources of bias affecting the results, especially from hypothetical, starting-point and strategic sources. Poorly conceived surveys and sketchy scenarios are especially prone to bias, although the development of best practice guidelines has helped to reduce this risk, particularly the NOAA panel report by Arrow et al. (1993). Practitioners must therefore ensure they take great care to ensure that they research and fully articulate the legal basis and likely ecosystem service impacts related to the scenario of developing a geothermal power project.

Practitioners may consider the third approach to be preferable to the second in cases where the development of a geothermal area is perceived to have a considerable impact on recreational amenity. In these cases, the use of the travel cost and contingent valuation methods in conjunction may be preferable to one overarching estimate of impacts to human well-being, as the travel cost method relies on standard economic techniques and actual behaviour rather than purely participants' responses to scenarios. The main disadvantage of the third approach is that it may overlook the use value associated with impacts to provisioning and regulating ecosystem services, albeit these may turn out to be very low in a project-specific context.

Irrespective of the quality of non-market valuation techniques and their input into cost-benefit analysis, their adoption remains symbolic of a weak sustainability paradigm, since the economic value of manufactured capital may exceed that of impacts to converted natural capital and related ecosystem services (Neumayer, 2003). The strong sustainability concepts of not breaching critical environmental thresholds are not captured within non-market valuation techniques, which focus on project-specific changes to the environment rather than their contribution to aggregate outcomes.

Environmental and sustainability impacts of geothermal power not considered by the ecosystem services perspective

The ecosystem service perspective extends the identification of environmental impacts to examine more deeply the effects on stakeholders and human well-being. It is a comprehensive approach, yet, in addition to economic impacts, two potential environmental impacts associated with the development of geothermal areas for power projects lie beyond its scope, as they relate to how energy is used rather than the products of ecosystem interactions. These are (1) land subsidence and earthquakes and (2) the sustainability of energy generation.

Land subsidence can occur when fluid and steam from underground reservoirs is extracted, leading to the sinking of the geothermal reservoir and potential impacts to buildings in surrounding areas of population (Shibaki and Beck, 2003). Induced seismicity associated with geothermal fields is increasingly common, especially due to the now widespread practice of re-injecting energy-depleted fluid to counteract pressure draw-down and ensure swift recharge (Deichmann and Giardini, 2009; Goldscheider and Bechtel, 2009; Flóvenz et al., 2015). Although typically small in scale, larger earthquakes could potentially damage production facilities and local infrastructure. The Geysers field in the United States experiences around twenty small quakes a year of between 2.0 and 3.0 on the Richter Scale, but two or three of more than 4.0 (Majer and Peterson, 2007).

Scenarios of industrial development of geothermal regions are rarely, if ever, described in a manner questioning the renewability of the geothermal resource. However, rates of pressure and temperature replenishment tend to be very slow, even allowing for the benefits of re-injection (Pritchett, 1998; Rybach et al., 2000; Stefansson, 2000; Rybach, 2003). Where unsustainable extraction of geothermal energy resources occurs, this will either lead to the cessation of industrial activities or, more probably, the further extraction of geothermal energy from adjoining fields (Cook et al., 2015). This is the likely situation facing the Hellisheiði Power Plant in Iceland, where high production density has resulted in significant pressure drawdown and decreased performance of wells (Gunnarsson and Mortensen, 2016). By definition, expanding the area of resource extraction means that the spatial scale and perhaps degree of ecosystem service impacts (particularly associated with noise, visual and recreational issues) is enlarged, and in ways that are very difficult to predict at the time that initial valuation studies and Environmental Impact Assessments are prepared.

Ecosystem services and other geothermal energy applications

This paper has focused on the typical ecosystem service impacts associated with the harnessing of geothermal energy, but particular to deep geothermal resources and their surface manifestations. The ecosystem service impacts associated with near-surface geothermal technologies, such as ground source heat pumps, will differ considerably due to the much lower temperatures and geological processes associated with resource extraction. These involve processes of geo-exchange typically at temperatures of 10 to 16 °C rather than geothermal power extraction at temperatures of between 75 and 300 °C.

Conclusion

Over the years, there have been many different approaches to valuing ecosystem service impacts: monetary, non-monetary, and a mixture of the two. This paper applied three criteria – scientific validity, reliability, and value commensurability – to determine whether each of the typical ecosystem service impacts associated with geothermal power projects should be valued using monetary or non-monetary information. Cost-benefit assessments should use non-market valuation techniques to estimate the economic value of ecosystem services impacts which are utilitarian in nature. In a geothermal energy context, these will typically include the sacrifice of provisioned resources (enzymes, genetic materials, silica etc.), recreational amenity, and cultural associations relating to non-use aspects of economic value. Non-monetary sources of information are especially important for estimating the value of cultural ecosystem services that have a decidedly philosophical leaning, such as aesthetical pleasure or spiritual enrichment gained from a geo-diverse setting, and form a necessary approach to ensure their proper arbitrage in a richer and more pluralist decision-making environment.

Environmental economists frequently conduct economic valuations of ecosystem service impacts, and yet they are typically ill-equipped to assess the degree of physical change. This paper considered the two main methods of describing environmental impacts for geothermal power projects – EIA and LCA – in order to determine their suitability for providing the required information. Existing LCA studies on geothermal power projects have omitted to consider socio-cultural impacts, although the advancement of social LCA offers the potential for a broader scope in the future. EIA studies on geothermal power projects have been closest to fulfilling the needs of environmental economists, encompassing the majority of ecosystem service impacts, yet further methodological progress is required to ensure that all project stakeholders are given voice and arbitrage in data-gathering processes.

Future academic research should focus on how best to incorporate an ecosystem services perspective into decision-making involving geothermal power projects, as well as the commencement of research into the economic value of impacts. Approving a geothermal power project which causes significant impacts to ecosystem services implies that the economic cost of the affected environment must be less than the financial gains of development, without ever attempting to quantify the value of these effects. Through the emergence of greater knowledge concerning the full cost of proposed geothermal power projects, the potential for sub-optimal decision-making is likely to reduce.

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5. Paper IV: Willingness to pay for the preservation of geothermal areas in Iceland – the contingent valuation studies of Eldvörp and Hverahlíð

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Willingness to pay for the preservation of geothermal areas in Iceland – The contingent valuation studies of Eldvörp and Hverahlíð

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ABSTRACT

Academic knowledge concerning preferences and willingness to pay for the preservation of geothermal areas is currently very limited. This paper seeks to increase understanding, using the contingent valuation method to estimate willingness to pay for the preservation of two high-temperature geothermal fields likely to be developed in the near future: Eldvörp and Hverahlíð. Both study sites are located in Iceland, a nation that has been the recipient of repeated calls by the OECD to commence accounting for environmental impacts in cost-benefit analyses, particularly those associated with power projects. We applied interval regression using log-transformation to estimate WTP for the preservation of the high-temperature Eldvörp and Hverahlíð fields. The estimated mean WTP was 8333 and 7122 ISK for Eldvörp and Hverahlíð respectively. Scaled up to the Icelandic population of national taxpayers, this equates to estimated total economic value of 2.10 and 1.77 billion ISK respectively. These results reinforce arguments in favour of accounting for environmental impacts of Iceland's future geothermal power projects as a mandatory component of the decision-making process. In Iceland and further afield, more research is necessary to develop understanding of the economic value of impacts to recreational amenity and other ecosystem services resulting from geothermal power projects.

1. Introduction

The approval of energy projects with significant environmental impacts implies that the economic costs of the affected environmental resources must be less than the financial benefits, but such irreversible decisions are frequently made without ever attempting to estimate the monetary value of the losses [1,2]. Consequently, an inequality in decision-making may occur, as Ruhl ([3]; p. 761) describes: *"failure to refine our understanding of their economic values, and the consequent inability to account for those values in regulatory and market settings and, more importantly, in the public mind, is unlikely to promote the preservation of natural systems."*

Until this paper, academic knowledge concerning preferences and willingness to pay for the preservation of geothermal areas has, for over three decades, been limited to the results published in a single paper, the contingent valuation study by Thayer [4]. Thayer applied the contingent valuation method to estimate willingness to pay to preserve the Santa Fe National Forest in New Mexico, which was a diverse, scenically attractive and popular recreational area blessed with hot springs, but potentially subject to development in order to provide energy for a geothermal power project. This study was illustrative of the land-management complexities commonly associated with harnessing geothermal resources for power projects, whereby all stages of the fuel cycle are located at the production site and a multitude of ecosystem services may have to be sacrificed through the development and operation of plant infrastructure and transmission lines [4,5].

In this paper, the total economic value of preserving two of Iceland's geothermal areas – Eldvörp and Hverahlíð – is estimated using the contingent valuation method (CVM). In the case of Eldvörp, the impacts are related to further exploratory drilling, which may or may not eventually lead to an application for a production license; for Hverahlíð, the contingent valuation scenario relates to impacts deriving from a proposed geothermal power plant. These study sites have been chosen as case studies for two

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main reasons: (a) they are characterised by a range of geomorphological features, contrasting levels of pre-existing human intervention on their landscape in pursuit of geothermal power and recreational pursuits, and their development will lead to environmental and social impacts which vary in type and degree; and (b) they are both listed as approved for development by the Iceland Master Plan for Nature Protection and Energy Utilisation,[1] the nation's legally binding strategic tool for identifying suitable energy projects. They thus represent credible scenarios for survey participants to respond to.

The outcomes from these studies are potentially of interest to anyone interested in decision-making connected to the development of geothermal power, and particularly practitioners of cost-benefit analysis. However, in the case of Iceland, there is also a decidedly practical relevance in terms of advancing the decision-making apparatus. All three of the OECD's Environmental Performance Reviews of Iceland have advocated the nation strengthening its use of economic analysis in decision-making [6–8]. In particular, the OECD's 2014 assessment emphasised that it was important for Iceland to *"develop some cost-benefit analysis process which gives appropriate consideration to all dimensions of power development (environment, tourism, social and regional development, project profitability)"* ([8]; p.115). In addition, Working Group 4, currently responsible for progressing the economic knowledge base underpinning the next iteration of Iceland's Master Plan for Nature Protection and Energy Utilisation, has argued that the macroeconomic impact of the nation's future energy projects can only be properly evaluated based on knowledge of all costs and benefits of projects, and these must include the economic value of their environmental impacts [9].

In recent years there has been heated debate in Iceland concerning the trade-off between environmental goods and power projects, most notably in the case of the multiple and long-lasting impacts to flora and fauna [10] associated with the controversial 690 MW Kárahnjúkar Hydropower Plant in eastern Iceland, which has been used since 2007 to supply electricity to Alcoa's Fjardaál aluminium smelter in Reyðarfjördur. However, to date, cost-benefit assessments for Icelandic energy projects have been undertaken without conducting total economic valuations to guide decision-making, ensuring that the monetary value of socially desirable goods, such as the qualities of an undisturbed landscape in a preserved geothermal area, have been overlooked [11,12]. Moreover, only a very few academic studies have been undertaken in Iceland involving the utilisation of non-market valuation techniques, and just two related to energy project, both contingent valuation studies on the Kárahnjúkar Hydropower Plant [13,14].

This paper has four main aims: (1) to enhance the currently scant academic literature concerning preferences and willingness to pay for the preservation of geothermal areas; (2) to provide a comparison of WTP to preserve high-temperature for geothermal areas of varying scale, environmental characteristics and impacts; (3) to begin to satisfy the OECD's oft-repeated call for the introduction of a suitable environmental accounting method for use within the cost-benefit assessments of future energy projects in Iceland; and (4) to communicate in detail a best practice case study of the CVM for future practitioners in Iceland to follow.

The structure of this paper is as follows. Section 2 of this paper begins by briefly summarising details about the regulative background and study locations for Eldvörp and Hverahlíð, before outlining the anticipated environmental and social impacts of their development. Section 3 sets out a detailed description of this paper's methodology, including the survey design and mode of statistical analysis. Section 4 outlines the results and discusses the main implications of the outcomes.

2. Legislative and regulatory background, project proposals and impacts

2.1. Legislative and regulatory background

The Iceland Master Plan for Nature Protection and Energy Utilisation began to be forged in the late 1990s. Its ambition was to provide a national strategic guide to aide decision-making concerning energy projects [15]. Closely akin to Strategic Environmental Assessment in terms of its land use planning objectives, its aim was to evaluate the suitability of various potential geothermal and hydro power projects, ranking and classifying these according to their environmental, socio-cultural and economic impacts [11,16,17]. Enshrined in law in 2013,[2] the Master Plan approved by the Icelandic Parliament segregated sixteen projects (2 hydro power, 14 geothermal) into the category of 'suitable for development', twenty (11 hydro power, 9 geothermal) as 'protected', and the remaining thirty-one (22 hydro power, 9 geothermal) as 'under consideration' pending further data and review [15]. The geothermal areas of Eldvörp and Hverahlíð were bracketed within the fourteen geothermal projects deemed 'suitable for development'.

2.2. Study site background and project proposals – Eldvörp and Hverahlíð

Eldvörp is a high-temperature field of 1007 ha, located on the Reykjanes peninsula, approximately 50 km south-west of the capital city of Reykjavík. Eldvörp is currently owned by the energy company, HS Orka, who have estimated the productive capacity of the area to be in the region of 50 MW_e [15]. Base on the results from a test well in 1983, HS Orka consider the field to have a productive capacity in the region of 50 MW_e. HS Orka have planning permission to carry out further exploratory research, involving the drilling of shallow and deep test wells. They intend to conduct shallow and deep drill testing on up to five further boreholes [18].

Hverahlíð is a high-temperature field of 320 ha, located approximately 25 km to the east of Reykjavík and 2 km south-east of the existing 303 MW Hellisheiði Power Plant. Owned by Reykjavík Energy, Hverahlíð is estimated to have a productive capacity in the region of 90 MW_e [15]. Reykjavík Energy currently holds a fifteen-year exploration license for the Hverahlíð area. Their project proposals include two 45 MW turbines, 18 production wells, with estimated steam consumption of around 80–85 kg/s each, and 9 re-injection wells. The main project components would also include the steam utility, freshwater utility, power plant, cooling towers, drainage utility, roads and tracks to connect to the nearby main highway, quarrying of material, facilities for contractors, and a connection with the transmission system [19].

2.3. Summary of environmental and social impacts – Eldvörp and Hverahlíð

An Environmental Impact Assessment, based on HS Orka's proposals for further exploratory research, was completed by VSO Consulting in 2013. A brief summary of the likely environmental impacts is provided as follows:

[1] Also referred to as the *Master Plan for Hydro and Geothermal Energy Resources* in Refs. [11,12].

[2] Law number 48/2011: http://www.althingi.is/lagas/141b/2011048.html.

- Noise impacts will be local and potentially impact negatively on the visitor experience. They are very likely to be in breach of regulations 724/2008 and 1000/2005, which state that noise in quiet rural areas should not exceed 40 dB (A). These effects will be reversible over time, although their duration will depend on the length of the testing phase.
- There are no plans to disturb the crater row itself, only surrounding lava fields. The project's proposals are, however, in breach of Article 37 of Iceland's Nature Conservation Act (no. 44/1999), as they will lead to irreversible damage to lava fields formed during the past 10,000 years.
- The current landscape contains multiple geological features, which contribute to the recreational and educational value of the area. The introduction of geothermal power projects in the area, even research ventures, will lead to uncertain impacts on the quality of the future visitor experience – for those seeking evidence of geothermal energy, it may be positive; for those preferring quiet natural environments largely devoid of human interventions, it may be very negative.
- Although Eldvörp includes human remains, the research proposals are not likely to directly affect the archaeological heritage of the area. The only negative impacts might relate to a reduction in the quality of the visitor experience due to the introduction of nearby boreholes.
- Impacts on the quality and availability of local groundwater resources are considered to be negligible.
- There are few birds living in the area so any impacts to these or other fauna are likely to be zero or negligible.
- The project will lead to disturbance of generally common moss vegetation where structures will be built, but given their nationwide abundance, the overall impacts are considered to be insubstantial [18].

In 2008, VSO Consulting prepared an Environmental Impact Assessment based on Reykjavík Energy's proposals for a future power plant at Hverahlíð. The likely impacts are summarised as follows:

- Calculations show that a noise level exceeding 45 dB will be audible at a distance of 1000 to 1,400 m from the steam chimneys, which is more than is commonly found at other outdoor recreational sites in Iceland.
- Insubstantial but very uncertain impacts to the sustainability of the geothermal reservoir at Hverahlíð.
- Insubstantial impacts on local geological formations – the hot springs formed in the last 10,000 years in the area will be protected in accordance with Article 37 of Iceland's Nature Conservation Act, number 44/1999.
- Landscape impacts may vary in degree between insubstantial and considerable – the proposals will lead to small reductions in the size of young lava fields and impinge on old trodden routes; the general visual impact of the proposals is likely to be quite high, as they affect previously untouched areas. A number of hikers, skiers and horse riders use the Hverahlíð area, and thus the value of the area for those enjoying these recreational pursuits will likely deteriorate for an irreversible period of several decades.
- Mitigating measures will be adopted in accordance with The National Heritage Act (107/2001) to ensure that the impact on three archaeological remains at Hverahlíð is insubstantial.
- Increased but insubstantial concentrations of hydrogen sulphide and greenhouse gas emissions.
- Insubstantial hydrological effects are anticipated, including groundwater resources – groundwater holes in Hverahlíð will provide a source of freshwater for the project and reinjection will be used to maintain the sustainability of these supplies.
- Insubstantial but uncertain impacts will occur on local fauna – there are few birds in the area but it is possible that micro-organisms living in the hot springs may be disturbed.
- The project will lead to disturbance of vegetation where structures will be built, but such plants and mosses are abundant nationwide and thus the overall impacts are considered to be insubstantial [19].

3. Methodology

3.1. Ecosystem services, the total economic value framework and contingent valuation method

Economists apply a utilitarian conception of value to estimate monetarily the value of ecosystem services – the various benefits human beings derive from environmental resources – in order to better understand their contribution to social welfare, and the potential impacts of changes in the quality or quantity of their provisioning [20,21].

A commonly used framework for examining the utilitarian value of ecosystem services is the concept of total economic value, an all-encompassing measure of the economic value of any environmental resource [21,22]. Economists have typically split the total economic value of natural resources into three main constituent parts: use value, option value, and non-use value. Use value includes direct use, indirect use and option value [23–25]. Non-use value is sourced from the knowledge that a resource is preserved, irrespective of an individual's planned or potential demand for its services [12,26], and is commonly broken down into three sub-components: existence value, bequest value and altruistic value [22].

It is evident when estimating marginal changes in the total economic value of any environmental resource, in all cases stated preference techniques, such as the CVM, should be utilised as they are the only means of estimating non-use value. Although currently poorly understood in a geothermal energy context, a considerable number of studies have highlighted the significance of this value component in other resource contexts [27–33].

A common theme of geothermal power projects is the simultaneous sacrifice of multiple cultural ecosystem services [12]. In cases such as Eldvörp and Hverahlíð, where this may be likely, the CVM can provide a very useful stand-alone estimate of marginal changes in total economic value. This approach contrasts with other non-market valuation techniques, such as the travel cost method, which are focused on recreational use value and not able to provide estimates linked to non-use value. The CVM was also used by Thayer [4] and negates the process of undertaking and aggregating outcomes from several non-market valuation techniques, which is frequently time-consuming, labour intensive and expensive.

3.2. Survey administration and design

Various instruments have been used to conduct contingent valuation surveys, including mail surveys, telephone surveys, face-to-face interviews, and mixtures of the aforementioned [34]. Different survey instruments come with various pros and cons in terms of costs, biases and participation rates [35–37]. Although the National Oceanic and Atmospheric Administration (NOAA) panel advocated the use of face-to-face interviews [38], in recent times web-based formats have become very popular [39,40,77]. Even though use of the internet to administer surveys is a relatively recent advancement, evidence has been found in the literature in support of the method in terms of statistically insignificant differences in mean and median WTP compared to other survey instruments [39,41].

This study adopted a web-based format for two main reasons. It was a cost-effective means of obtaining a large sample – in 2015, the most recent year of data availability, 96% of the Icelandic population had access to the internet [42]. The web-based survey format also provided considerable opportunities and advantages in terms of design. As well as communicating a straight-forward, interactive and visually amenable style of presentation, participants were not able to browse through the surveys and answer questions in the wrong order. The surveys were interactive and branched to a considerable extent, so that participants did not have to respond to questions that were irrelevant to them based on their previous answers. In addition, the use of a web-based survey was particularly useful for randomising the bid offers in a manner which ensured that no participants were aware of this underlying process.

The surveys were implemented by the University of Iceland's Social Science Research Institute, who possess an internet panel of over 11,000 participants. These individuals are selected at random from the national registry to ensure they are representative of the Icelandic population and to prevent self-selection. Prior to implementation, the surveys were tested through two small pilot studies of fifty participants. Next two separate draws from the internet panel were undertaken, ensuring that participants completed either the Eldvörp or Hverahlíð survey, never both. The surveys were open for four weeks during April 2016. In this period, those who had not participated within a few days of an initial email were sent a reminder. A total of 474 and 448 responses were attained for the Eldvörp or Hverahlíð surveys respectively. These samples were found to be highly representative of the Icelandic population in terms of gender balance, age, number of children, marital status, and income, with comparable proportions to those identified within the most recent Icelandic Census, held in 2011.

The contingent valuation component of the web survey was designed with the objective of being in accordance with the various best practice guidelines set out by Arrow et al. [38]; Carson [43]; Carson et al. [35]; Carson and Groves [44]; Kling et al. [45]; and Haab et al. [46]. The web survey included three sections.

In the first section, participants were asked a series of attitudinal questions concerning the environment and society in Iceland. Participants were asked to select from a list of nine options the issues they considered to be the most and least pressing for Icelandic society to address. Next, they were asked to state their degree of agreement[3] with nine clearly defined statements. These covered attitudes relating to the national importance of economic diversification; economic growth; harnessing untapped renewable energy resources; protecting areas of environmental value; paying monetarily for the preservation of environmentally valuable areas and evaluating monetarily the impacts of developments in such areas; and whether recreational amenity must always be sacrificed following construction of a geothermal power plant. Finally, the first section concluded by asking participants to select from a list of 15 options (including 'other') the activities they had carried out during outdoor excursions in Iceland over the past year.

The second section questioned participants about their familiarity with Eldvörp or Hverahlíð. They were asked if they had ever visited the study sites and, based on that answer, they either received a question about their activities or if they intended to visit in the future. Participants were then provided with the respective contingent valuation scenarios for the study sites, which included details of the likely environmental impacts of the project proposals. Following this, participants were reminded about their budget constraint and asked whether they were for or against the preservation of their study site, much like the approach in referendum voting [45]. Individuals expressing a preference for preservation were presented with double-bounded WTP questions and validity checks afterwards to assimilate their understanding of their scenario. Individuals who were against preservation of their study site were forwarded to questions designed to sort protest voters from those with a pure preference against preservation.

The third and final part of the survey, as is customary, was comprised of socio-economic questions in order to ascertain factors influencing WTP. These questions were issued at the very end of the survey since they have the potential to stimulate a state of objection amongst participants, leading to non-responses [35].

3.3. Scenario description and payment vehicle

In contrast to normal opinion polls, contingent valuation surveys include a detailed description of a scenario that essentially constructs a hypothetical market for participants [43]. However, it is vital that the hypothetical market is kept as real [47] and consequential [44] as possible to limit the effects of bias on welfare estimates. As these studies were based on pre-existing designs and their likely environmental impacts had already been determined, the risk of hypothetical bias was much reduced compared to a purely theoretical scenario. Participants were carefully reminded that Eldvörp and Hverahlíð have both been deemed potentially suitable for development by the Iceland Master Plan for Nature Protection and Energy Utilisation. Both surveys provided participants with a detailed description about the study sites, their ownership in terms of current licensing arrangements, environmental characteristics, likely developments in pursuit of geothermal power, and the environmental impacts pertaining to these proposals. Environmental impacts were described in accordance with the content in Section 2.3 of this paper and summarised using non-technical language to maximise the likely understanding of participants. In order to alleviate potential land management conflicts between utilisation and preservation desires, the scenarios proposed that national legislation could potentially be enacted to ensure that the areas were preserved. However, participants were informed that due to the forgone future economic benefits suffered by the license holders, a financial payment would be required to secure the sites' preservation.

In recent years, considerable focus has been allocated to the overall valuation process, with due recognition that WTP estimates are strongly influenced by the procedures through which the resource is provided and how the payment is made [37,48,49]. A realistic and neutral choice of payment vehicle can be incentive compatible [35,37,50,51]. In this study, the chosen payment vehicle was an additional lump-sum tax, payable only once and charged to all taxpayers aged over 18 years in Iceland irrespective of income. This choice was made due to its incentive compatibility compared to voluntary arrangements and the technical infeasibility of charging entrance fees. Its design was very similar to other lump-sum taxes in Iceland, such as the annual fixed levy towards the state television and radio production.[4] Assuming that participants believed in the survey's scenario, the design of the tax and knowledge that it would be levied irrespective of income

[3] On a scale of 1–5, with 1 = strongly agree; 2 = somewhat agree; 3 = neither agree nor disagree; 4 = somewhat disagree; and 5 = strongly disagree.

[4] The levy for broadcasting services was 16,400 ISK for the 2015 tax year and was required to be paid by all individuals of at least 18 years of age with taxable income [73].

minimised the risk of strategic bias influencing the welfare estimates.

Based on the results from the pilot studies and recent focus groups concerning the significance of these study sites, the affected population for the surveys was considered to be the entire nation. Since the payment vehicle used to elicit WTP was an additional lump-sum tax, the affected population became all taxpayers in Iceland.

3.4. Elicitation of WTP and statistical model

There are many different ways of eliciting WTP estimates using contingent valuation surveys. A variety of methods have been advocated in previous studies: open-ended questions [52], payment cards [53], dichotomous choice (single, one and a half, or double bounded) [38,54–56], iterative bidding games [57] and referendums [58]. Dichotomous choice has proven to be a very widely adopted elicitation formation, mainly due to its simplicity of use in data collection. In this study, we adopted the double bounded model due to its greater statistical efficiency and reduced coefficient variance compared to the single bounded version [59]. In the double bounded approach, participants with WTP are asked a closed-ended question twice in relation to bid offers. If the answer to the first question was 'no' then the second question offered a lower bid (t_i^L); if the answer to the first question was 'yes' then a higher bid was communicated (t_i^U) [59].

When using the double bounded elicitation format, Cameron and Quiggin [60] contend that as the second bid depends on the first bid, the two bid levels are dependent, leading to the first bid 'anchoring' WTP. The general explanation for 'anchoring' is that the first bid value provides participants with the psychological impression that the quantity to be estimated could be near this value [61]. In this study, efforts to increase the accuracy of the WTP distribution across the survey sample as a whole were undertaken by randomly varying the bid amounts, helping to reduce the possible influence of starting-point bias [62].

In the statistical model, a participant's WTP is represented as function of several determining variables, including socio-economic characteristics and individual preferences. If WTP is assumed to be a linear function, a participant's WTP is expressed by equation (1):

$$Y_i = \alpha - bt_i + x_i'\beta + \mu_i \tag{1}$$

Where Y_i denotes the WTP of respondent i; x_i' is a predictor variable vector that represents an individual's socio-economic characteristics; t_i is the bid amount; α, b and β are the parameters to be estimated; and μ_i is an error term relating to unobserved factors. Each participant responds either 'yes' or no' to the bid amount t_i to represent their WTP, and this enables a determination of whether participant i's valuation is larger than t_i. Through the use of an indicator variable, y_i, the probability that a participant will answer 'yes' ($y_i = 1$, indicating $Y^i > t_i$) or 'no' ($y_i = 0$, indicating $Y^i < t_i$) can be represented by equations (2) and (3) respectively:

$$\Pr(y_i = 1|X_i) = \Pr(Y_i \geq t_i) = 1 - G_Y(t_i) \tag{2}$$

$$\Pr(y_i = 0|X_i) = \Pr(Y_i < t_i) = G_Y(t_i) \tag{3}$$

In equations (2) and (3), $G_Y(t_i)$ refers to the cumulative density function of the participants' WTP. In the double bounded dichotomous choice model, participants are divided into four groups, as per the approach set out in Alberini [63]; Haab and McConnell [64]; and Aravena et al. [65]. In this study, we apply a zero-truncated spike model [66] for instances of true zero WTP,[5] in so doing forming a fifth group. For each individual i with WTP (including true zero WTP), a binary-valued indicator represents whether the individual belongs to one of the five groups set out in equation (4):

$$\begin{aligned}
I_i^{YY} &= 1 \ \text{if WTP} \geq t_i^U (0 \ \text{if otherwise})\\
I_i^{YN} &= 1 \ \text{if } t_i \leq \text{WTP} < t_i^U (0 \ \text{if otherwise})\\
I_i^{NY} &= 1 \ \text{if } t_i^L \leq \text{WTP} < t_i (0 \ \text{if otherwise})\\
I_i^{NN} &= 1 \ \text{if } 0 < \text{WTP} < t_i^L (0 \ \text{if otherwise})\\
I_i^{ZERO} &= 1 \ \text{if WTP} = 0 (0 \ \text{if otherwise})
\end{aligned} \tag{4}$$

Where: t_i denotes the initial bid; t_i^U and t_i^L denote the second bids; I_i^{YY} a participant accepting both bid offers; I_i^{YN} a participant accepting the first and rejecting the second bid offer; I_i^{NY} a participant rejecting the first and accepting the second bid offer; I_i^{NN} a participant rejecting both bid offers; and I_i^{ZERO} a participant with true WTP of zero.[6]

Following the approach of Cameron and Huppert (1989) [78], interval regression was applied to the groups expressed in equation (4). The log-likelihood of the model is represented by equation (5):

$$\begin{aligned}
LL = &\sum_{i=1}^{N_{yy}} yy \log(prob(yy)) + \sum_{i=1}^{N_{yn}} yn \log(prob(yn))\\
&+ \sum_{i=1}^{N_{ny}} ny \log(prob(ny)) + \sum_{i=1}^{N_{nn}} nn \log(prob(nn))\\
&+ \sum_{i=1}^{N_{zero}} zero \log(prob(zero))
\end{aligned} \tag{5}$$

where yy, yn, ny, nn and zero represent the responses of the individual and N_{yy}, N_{yn}, N_{ny}, N_{nn} and N_{zero} correspond to the number of occurrences of each response type. Assuming that the cumulative density function $G_Y(t_i)$ follows a logistic distribution, consequently double bounded dichotomous logit models were estimated. The models in this paper were estimated with respect to covariates to study the determinants of WTP.

4. Results and discussion

4.1. Responses to attitudinal questions and outdoor activities in Iceland

For the purposes of the first section of the surveys only, focused on attitudes and outdoor behaviour, the results are combined ($n = 922$) since these questions did not relate specifically to either study site. Table 1 outlines these results. The issues of improving healthcare (39.15%) and securing affordable housing to rent or buy (20.82%) stood out as being by far the most pressing societal concerns. Protecting important natural areas, their habitats and wildlife (12.26%) was of third greatest concern. The selection of the least pressing issue appeared dominated by uncertainty, with 16.16% of participants selecting the 'don't know' response and a further 4.66% opting not to answer. Of those who selected a pre-defined option, waste management (16.16%), economic growth (15.15%) and

[5] As opposed to instances of protest-led zero WTP, which were excluded from the model.

[6] This study did not extend the distribution to include negative WTP values, since WTP studies provide very poor approximations of negative WTP or willingness to accept (WTA) compensation. Instead, these participants, in line with the approach advised by several scholars, were allocated a WTP of zero on the basis of an assumed genuine indifference between the preservation and development of Eldvörp or Hverahlíð [66,74–76].

Table 1
Most and least pressing issues for Icelandic society to address.

Response	Most Pressing		Least Pressing	
	Frequency	Percentage	Frequency	Percentage
Affordable housing to buy or rent	192	20.82	56	6.07
Reducing air pollution	36	3.90	53	5.75
Reducing water pollution	9	0.98	71	7.70
Improving educational quality	41	4.45	42	4.56
Economic growth	58	6.29	142	15.40
Diversifying the economy	64	6.94	103	11.17
Protecting important natural areas, their habitats and wildlife	113	12.26	37	4.01
Improving waste management	6	0.65	149	16.16
Improving healthcare	361	39.15	30	3.25
Don't know	29	3.15	196	21.26
Chose not to answer	13	1.41	43	4.66
Total	**922**	**100.00**	**922**	**100.00**

economic diversification (11.17%) were deemed the least pressing societal concerns. Few members of the sample considered improving healthcare (3.25%) or protecting important natural areas, their habitats and wildlife (4.01%) to be their least pressing issue.

More specific insight into societal attitudes was obtained through responses to nine statements focused generally on conflicts between further economic development and environmental preservation, particularly related to the further deployment of Iceland's renewable energy resources and associated decision-making processes. These are displayed in Table 2, with percentages provided in parentheses.

Although not considered to be the most pressing issues for Icelandic society to address (see Table 1), there was consensus that economic diversification and economic growth were still important issues, with 77.65% and 74.52% of the sample voicing either strong or slight agreement. Studies have shown that Iceland's economic growth has been intrinsically linked to the utilisation of its renewable energy resources [67,68], yet opinion was mixed concerning whether the harnessing of untapped sources of renewable energy was important, with 41.44% and 32.21% of the sample strongly agreeing/slightly agreeing and strongly disagreeing/

Table 2
Attitudes to socio-economic and environmental statements.

Statement	Response (n = 922)					
	Strongly agree (1)	Slightly agree (2)	Neither agree nor disagree (3)	Slightly disagree (4)	Strongly disagree (5)	Chose not to answer
The diversification of the Icelandic economy is important	349 (37.85)	367 (39.80)	160 (17.35)	31 (3.36)	8 (0.87)	7 (0.76)
The growth of the Icelandic economy is important	288 (31.24)	399 (43.28)	177 (19.20)	40 (4.34)	11 (1.19)	7 (0.76)
It is important that Iceland continues to harness its untapped renewable energy resources	159 (17.25)	223 (24.19)	226 (24.51)	155 (16.81)	142 (15.40)	17 (1.84)
Areas in Iceland that I consider to be of significant environmental value should always be protected from development	448 (48.59)	276 (29.93)	127 (13.77)	44 (4.77)	19 (2.06)	8 (0.87)
For natural areas in Iceland that I visit and enjoy, I would be willing to make a monetary payment to ensure their protection from development	166 (18.00)	277 (30.04)	276 (29.93)	97 (10.52)	70 (7.59)	36 (3.90)
For natural areas in Iceland that I rarely visit or enjoy but still regard as being important, I would be willing to make a monetary payment to ensure their protection from development	154 (16.70)	245 (26.57)	290 (31.45)	111 (12.04)	84 (9.11)	38 (4.12)
The economic benefits of harnessing Iceland's geothermal and hydro power energy resources are more important than the protection of affected natural areas	37 (4.01)	124 (13.45)	246 (26.68)	215 (23.32)	263 (28.52)	37 (4.01)
Before Iceland's energy projects are approved for development, it is important that the National Energy Authority evaluates the economic value of their environmental impacts	391 (42.41)	354 (38.39)	117 (12.69)	22 (2.39)	21 (2.28)	17 (1.84)
It is possible for a geothermal field to be used for power generation and still provide the same or similar level of recreational benefits as before the power plant is constructed	178 (19.31)	303 (32.86)	239 (25.92)	109 (11.82)	61 (6.62)	32 (3.47)

slightly disagreeing respectively. Almost half of the sample (48.58%) were in strong agreement with the statement that Iceland's environmentally valuable resources should be protected from development. Moreover, only 17.46% strongly or somewhat agreed (51.84% somewhat or slightly disagreed) with the notion that the economic benefits of harnessing Iceland's geothermal and hydro power resources are of greater importance than the protection of natural areas. There was broad agreement about the importance of the National Energy Authority (Orkustofnun) evaluating the environmental impacts of energy projects in terms of their economic value, with almost 80.80% of the sample voicing some level of agreement with this statement, although the subject matter of this survey may have influenced this outcome. In terms of paying for the protection of natural areas in Iceland, less than half the sample (48.08%) either strongly or slightly agreed with the notion that they should pay for the protection of natural areas that they have visited and consider valuable.

Finally, in Section 1, participants stated the activities they have carried out during outdoor excursions in Iceland over the past year. The five most commonly listed activities were hiking (782/922), swimming (536/922), mountaineering (433/922), cycling (396/922), and berry picking (377/922).

4.2. Visitor data for Eldvörp and Hverahlíð

A total of 146 (30.80%) and 202 (45.09%) participants stated that they had visited Eldvörp and Hverahlíð respectively. The proximity of Hverahlíð to Iceland's Route 1, the island's main highway, probably explains the higher frequentation associated with this site. Of the 328 participants who had not visited Eldvörp, a further 224 (47.26%) asserted that they were likely to in the future. For Hverahlíð, 149 (33.26%) of participants stated that they planned to visit the site in the future. Similar proportions of the samples claimed to have no intention to visit the sites in the future – 98 (20.68%) and 94 (20.98%) for Eldvörp and Hverahlíð respectively. Nine participants across the two samples were unclear about their future intentions.

The sub-sample of participants who had visited the study sites were asked to tick the various activities they had enjoyed. In the case of Eldvörp, the most commonly stated activities were hiking (126 participants, 86.30%) and photography (108 participants, 73.97%). Hiking was also a popular pursuit at Hverahlíð, enjoyed by 150 (74.26%) participants, whilst cycling and skiing were both listed by 44 (21.78%) members of the sub-sample.

4.3. Willingness to pay for preservation of Eldvörp and Hverahlíð

Following the scenario description, all participants were asked if they were prepared to pay a one-time lump sum tax to preserve Eldvörp or Hverahlíð. Table 3 sets out the responses, with percentages in parentheses. Compared to the Hverahlíð study, 8.60% more participants from Eldvörp's sample expressed WTP.

Of the sub-sample of 264 participants who were WTP for Eldvörp's preservation, 89 (33.71%) had visited the site previously, whilst a further 136 (51.52%) intended to in the future. Only 36 (13.64%) participants expressed WTP and had neither visited Eldvörp nor intended to in the future. For Hverahlíð, 94 (44.55%) of the 211 participants with WTP had visited the site, and a further 87 members (41.23%) were likely to do so in the future. The remaining 30 participants (14.22%) were willing to pay, but had neither visited Hverahlíð nor stated that they were likely to do so in the future.

Participants who were not willing to pay were asked to state their reason to determine whether they were protest voters, who needed to be dropped from the results, or had a genuine WTP of zero. Protest voters were identified if their reasoning related to objections about paying higher taxes in Iceland or if they voiced strong discontentment concerning energy development in their study area. A genuine WTP of zero was determined on the basis of either insufficient disposable income to pay the tax (but otherwise an intention to preserve) or a clearly stated indifference between the preservation of the site and scenario of energy development. In these surveys, the number of protest voters was fairly high, corresponding to 151 of 210 participants (71.90%) in the case of Eldvörp and 175 of 237 participants (73.84%) for Hverahlíð. The majority of protest voters (65.33% of participants across the two samples) were against the paying of higher taxes for the preservation of these sites. The high number of protest voters was likely exaggerated by the political turmoil occurring during the launch of the surveys in April 2016, which involved considerable anti-government sentiment. At this time, the largest political protests in Icelandic history were occurring in connection to various financial irregularities revealed by the Panama Papers expose, which ultimately led to the resignation of the prime minister. There were 57 and 55 instances of genuine zero WTP for Eldvörp and Hverahlíð respectively, and these participants were accounted for using the spike model.

4.4. Bid elicitation responses

All participants expressing WTP were moved on to the bid elicitation stage. The first bid offers were randomly allocated to participants from the following options: 1000 ISK; 2000 ISK; 3000 ISK; 4000 ISK; or 5000 ISK. If a participant answered 'yes' to the first binary question, then their second bid was higher and one of the following: 2000 ISK; 4000 ISK; 6000 ISK; 8000 ISK; or 10,000 ISK. Participants answering 'no' to the first binary question received lower bid offers from this pool: 500 ISK; 1500 ISK; 2500 ISK; 3500 ISK; or 4500 ISK.

Table 4 identifies the numbers who accepted or rejected the first bid, and the participants who then proceeded to accept or reject the second bid. Percentages are provided in parentheses.

It is evident that 76.43% of participants in the Eldvörp survey answered 'yes' to the first bid, but slightly under half (49.75%) of these individuals were subsequently affirmative of the second bid. Proportionally, 23.57% of the Eldvörp sample rejected the first bid and 12.17% answered 'no' to both bid offers. Broadly similar patterns were evident in the case of the Hverahlíð survey, with

Table 3
Willingness to pay for preservation of Eldvörp or Hverahlíð

WTP Tax	Eldvörp	Hverahlíð
Yes	264 (55.70)	211 (47.10)
No	210 (44.30)	237 (52.90)
Total	**474 (100.00)**	**448 (100.00)**

Table 4
Summary of first and second bid responses for Eldvörp[a] and Hverahlíð surveys.

		Second bid (Eldvörp/Hverahlíð)		
		Yes	No	Total
First bid (Eldvörp)	Yes	101 (38.40)	100 (38.02)	201 (76.43)
	No	30 (11.41)	32 (12.17)	62 (23.57)
	Total	**131 (49.81)**	**132 (50.19)**	**263 (100.00)**
First bid (Hverahlíð)	Yes	88 (41.71)	78 (36.97)	166 (78.68)
	No	24 (11.37)	21 (9.95)	45 (21.32)
	Total	**112 (53.08)**	**99 (46.92)**	**211 (100.00)**

[a] In the case of Eldvörp, one participant expressed WTP but then failed to complete the bidding process, leading to their exclusion from any results discussed henceforth.

Table 5
Predictor variables and coding.

Predictor variable	Explanation of coding
Gender	A dummy variable, with 0 = female and 1 = male.
Age	Age was the stated age based on participants' date of birth.
Residence	A dummy variable, with 0 = a person living outside of a 100 km radius surrounding Reykjavik and 1 = a person living inside this boundary. The 100 km demarcation was determined to establish the influence on WTP of a person living within reasonable day-trip travelling distance of the sites.
Education	A dummy variable, with 0 = no form of degree education and 1 = a participant having completed at least an undergraduate programme.
Job market participation	A dummy variable, with 0 = a participant not actively involved in the labour market and 1 = an active participant. Those not actively involved encompassed students, the retired, sick or disabled individuals, carers, people on maternity/paternity leave, and the unemployed. Active participants included all employed and self-employed individuals, irrespective of whether these duties were part or full-time.
Number of children	Coded on a scale of 0–6 and related to the participant's number of children aged under 18.
Number in household	Coded on a scale of 0–7 and related to how many people lived in the participant's home, including themselves.
Marital status	A dummy variable, with 0 = not married, cohabitating or in a relationship, and 1 = married, cohabitating or in a relationship.
Disposable income	Classified according to five separate dummy variables. This was because response omissions were particularly evident in connection to the question about disposable income, and in order to maintain as many respondents in the sample used for the regression model, dummy variables were established for each of the income categories – Income dummy 1 = 200,000 ISK or less; Income dummy 2 = 201,000 –300,000 ISK; Income dummy 3 = 301,000–400,000 ISK; Income dummy 4 = 401,000–600,000 ISK; and Income dummy 5 = more than 600,000 ISK. For all five dummy variables, a value of 0 = not applicable and 1 = applicable.

Table 6
Summary of Predictor Variables – Eldvörp and Hverahlíð

Predictor variable	Eldvörp		Hverahlíð	
	For preservation (n = 264)	Genuine zero WTP (n = 57)	For preservation (n = 211)	Genuine zero WTP (n = 55)
WTP:				
Lower bound	4485 (2903)	0	4654 (3020)	0
Upper bound	6061 (2889)	0	5955 (3012)	0
Socio-demographic:				
Gender	0.43 (0.50)	0.42 (0.50)	0.39 (0.49)	0.64 (0.49)
Age	50.75 (17.61)	51.71 (15.01)	52.20 (17.23)	51.09 (17.67)
Residence	0.68 (0.47)	0.51 (0.50)	0.72 (0.45)	0.67 (0.47)
Education	0.45 (0.48)	0.36 (0.49)	0.45 (0.50)	0.35 (0.48)
Job market participation	0.66 (0.48)	0.63 (0.49)	0.69 (0.46)	0.60 (0.49)
Number of children	0.69 (1.06)	0.81 (1.16)	0.71 (1.14)	0.76 (1.17)
Number in household	2.83 (1.39)	2.88 (1.46)	2.89 (1.44)	3.00 (1.63)
Marital status	0.72 (0.45)	0.80 (0.40)	0.75 (0.43)	0.78 (0.42)
Income dummy 1	0.19 (0.39)	0.25 (0.43)	0.17 (0.37)	0.09 (0.29)
Income dummy 2	0.20 (0.40)	0.16 (0.37)	0.23 (0.42)	0.31 (0.47)
Income dummy 3	0.17 (0.38)	0.19 (0.40)	0.21 (0.41)	0.07 (0.26)
Income dummy 4	0.20 (0.40)	0.16 (0.37)	0.18 (0.38)	0.25 (0.44)
Income dummy 5	0.10 (0.30)	0.18 (0.38)	0.09 (0.28)	0.09 (0.29)
User:				
Visitor	0.34 (0.47)	0.35 (0.48)	0.45 (0.50)	0.40 (0.49)

marginally higher (by 3.31%) and lower (by 2.22%) percentages accepting or rejecting both bid offers respectively.

4.5. *Summary of predictor information and socio-demographic characteristics*

For each predictor variable, the mean outcome is provided with standard deviations in parentheses. The socio-demographic and user variables were coded as per Table 5:

Table 6 outlines the descriptive statistics for the regression model's predictor variables, grouped according to whether participants were for or against preservation. For most of the predictor variables, only negligible differences were apparent between the sub-samples who did and did not express WTP for preservation of their study site. In both surveys, there was a gender imbalance in who was willing to pay – 57% and 61% of respondents with WTP were female for Eldvörp and Hverahlíð respectively. Living within a 100 km radius of Reykjavik was more commonly associated with an expression of WTP than genuine zero WTP, by margins of 17% and 5% for the Eldvörp and Hverahlíð samples respectively. For both studies, 45% of the sub-samples with WTP possessed at least an undergraduate degree, whereas only 36% and 35% of those with genuine zero WTP had commensurable educational attainment. The declared disposable income statistics did not always match well with participant's stated reasons for possessing a genuine WTP of zero. In the case of the Eldvörp study, a quarter of participants voicing a genuine WTP of zero fell into the lowest income category of less than 200,000 ISK, which was 6% more than the corresponding proportion for those expressing WTP. However, in contrast, 18% of the sub-sample with genuine zero WTP had disposable income of greater than 600,000 ISK, the highest category, some 8% more than the corresponding grouping for those expressing WTP.

4.6. *Interval regression models*

The results from the two interval regression models are shown in Table 7. Standard errors are shown in parentheses. Due to a small number of cases (24 across both samples) whereby participants failed to answer the socio-demographic questions, the eventual sample numbers were 247 and 203 for Eldvörp and Hverahlíð respectively.

Table 7
Interval regression results – Eldvörp and Hverahlíð.

Variables	Eldvörp	Hverahlíð
Socio-demographic:		
Gender	0.312 (0.157)**	0.133 (0.180)
Age groups	0.044 (0.079)	−0.036 (0.103)
Residence	0.129 (0.154)	0.344 (0.185)*
Education	0.341 (0.161)**	0.351 (0.191)*
Job market participation	0.152 (0.187)	0.000 (0.207)
Number of children	0.074 (0.123)	−0.011 (0.123)
Number in household	−0.035 (0.100)	0.028 (0.102)
Marital status	−0.189 (0.188)	−0.038 (0.225)
Income dummy 1	0.129 (0.280)	−0.122 (0.343)
Income dummy 2	0.183 (0.262)	0.219 (0.309)
Income dummy 3	0.460 (0.263)*	0.093 (0.315)
Income dummy 4	0.484 (0.259)*	0.215 (0.317)
Income dummy 5	0.826 (0.324)**	0.279 (0.384)
User:		
Visitor	0.074 (0.154)	0.419 (0.182)**
Constant	7.861 (0.448)***	8.022 (0.522)***
σ	0.964 (0.069)	1.023 (0.084)
N	247	203
Log-likelihood	−277.946	−231.76
LR Chi^2	36.95	22.95
Prob > Chi^2	0.0007	0.0611

***indicates significance at the 1% level, ** significance at the 5% level, and * significance at the 10% level.

Table 8
Mean WTP for the preservation of Eldvörp and Hverahlíð.

	Mean WTP (ISK)	Standard deviation (ISK)	95% confidence interval (ISK)	
Eldvörp (n = 304)	8433	6246	7728	9138
Hverahlíð (n = 258)	7122	7270	6231	8013

Relatively few predictor variables were statistically significant in either model. Gender, education and income dummy 5 (>600,000 ISK) were significant at the 5% level in the Eldvörp model, whilst being a visitor was the only predictor with this level of significance in the Hverahlíð study. Other variables significant at the 10% level were two of Eldvörp's income dummy variables (3 and 4), and residence and education in the Hverahlíð model.

4.7. Mean and total WTP estimates

Building on the results of the models shown in Table 7 and incorporating the spike model, the mean results for Eldvörp and Hverahlíð are set out in Table 8. Table 9 provides an estimate of the total economic value of the Eldvörp and Hverahlíð by up-scaling the mean values by the deemed affected population, the total number of Icelandic tax payers. The total economic values are 2.10 and 1.77 billion ISK for Eldvörp and Hverahlíð respectively.

These values have been formed in response to the specific scenarios of environmental impact described in Section 2.3. As some environmental impacts were deemed to be uncertain in the respective EIAs, the WTP responses and scaled-up outcomes occur in the light of this unpredictability. WTP responses would likely have varied given alternative survey formats and scenarios of environmental change. Indeed, the communication of different project design parameters, environmental impacts and mitigation measures might have led to markedly different outcomes. Furthermore, the extent to which members of the public, often not well-versed about environmental issues, understood the consequences of simultaneous environmental consequences, some short and others long-term, is not known. Nor do these outcomes provide information about the environmental impacts which participants classed to be the most severe.

4.8. Economic valuation and Icelandic decision-making

As the OECD have repeatedly advised and Working Group 4 of Iceland's Master Plan recently requested, Iceland should commence an accounting process that enables traditional cost-benefit analyses to be extended to account for the full cost of proposed power projects. In this paper, a methodology has been delineated to fulfil these calls and two pilot contingent valuation studies conducted on likely forthcoming projects, expanding national and international knowledge of the total economic value of geothermal areas. The total economic value of the Eldvörp and Hverahlíð geothermal areas is considerable. To place these estimated costs into some sort of context and scale, 2.10 and 1.77 billion ISK are approximate to 2% of the estimated total construction costs of US $ 800,000,000 for Iceland's largest geothermal power plant at Hellisheiði [69]. They are thus of sufficient scale to provide ballast to the OECD and Working Group 4's respective calls for these values to be included within cost-benefit analyses.

As knowledge increases, a further challenge is apparent in the form of embedding accounting procedures into Iceland's decision-making processes. A considerable layer of discretion remains in Icelandic decision-making related to all development projects, and particularly those involving energy resources. Currently, in order for Icelandic energy projects to be granted licenses for exploration or production, they must be approved by the Master Plan and Orkustofnun, the National Energy Authority, needs to be satisfied that the proposals are compliant with regards to various legislation, including the Planning and Building Act (73/1997), Nature Conservation Act (44/1999) and Environmental Impact Assessment Act (106/2000) [11,70]. With regards to the latter, developers are required to undertake a comprehensive evaluation of an energy project's likely environmental and social impacts. The administration of this Act is conducted by Skipulagsstofnun, the National Planning Agency, who then issue a non-binding legal opinion on the project for Orkustofnun to consider. Cook et al. [11] contend that this approach risks the formation of a ‘regulatory gap’, whereby a project's negative environmental and social impacts, which are entirely qualitative in nature, are afforded insufficient arbitrage in decision-making. The authors cite the example of the Kárahnjúkar Hydropower Plant,[7] using this example to argue that *“failure to also quantify these impacts in monetary terms can therefore lead to project approvals that undermine social welfare”* and thus it is important *“to ensure standardisation of all costs and benefits related to projects”* ([11]; p. 110).

A policy agenda is already in place to encourage the sustainable utilisation of Iceland's renewable energy resources – in 2013, the Master Plan was enshrined in law, and since 1994 all energy projects have been required to carry out Environmental Impact Assessments. As this study has communicated, the environmental impacts associated with geothermal power projects approved by the Master Plan may appear relatively inconsequential when outlined in qualitative terms, but considerable when translated into economic values. Failure to standardise the environmental impacts of geothermal power may leave such costs insufficiently

[7] This project was rejected in the opinion provided by Skipulagsstofnun on the grounds of its environmental impacts, but the project was approved by Orkustofnun. The impacts included the permanent loss of habitats suitable for the breeding and nesting of reindeer, pink-footed geese and harbour seals; widespread soil erosion; loss of vegetation with a high conservation value; fragmentation and disruption of one of the last wilderness areas in Europe; and loss of one of Iceland's most popular glacial canyons, Dimmugljúfúr [10].

Table 9
Total WTP for the preservation of Eldvörp and Hverahlíð.

	Mean WTP (ISK)	Population of taxpayers (2015)	Total WTP (ISK)
Eldvörp	8433	249,094	2.10 billion
Hverahlíð	7122	249,094	1.77 billion

represented and the true social welfare implications of projects undetermined.

4.9. *Valuing the ecosystem services of geothermal areas, challenges and future research*

As per the inaugural study by Thayer [4]; in estimating the total economic value of preserved geothermal areas, this paper has not explored the economic value of the individual ecosystem services deriving from such environments. This paper has not delved into the constitutional components of total economic value and the economic impacts of changes in their provisioned quantity or quality. In so doing, it has been assumed that participants can assimilate all of the impacts to ecosystem services described within the respective Environmental Impact Assessments for the study sites to arrive at a single estimate of economic value for preservation. This may be a straight-forward consideration for disturbances to popular features of recreational value such as caves, ancient lava fields or footpaths, but is perhaps less easy when the estimate must also reflect impacts to the more intangible cultural ecosystem services associated with geothermal areas, such as landscape aesthetics. Furthermore, in some cases the impacts described in the Environmental Impact Assessments were set out in uncertain terms, leading to a lack of clarity concerning the degree of qualitative change.

The academic literature is devoid of any studies providing a holistic yet structured economic assessment of the impact of a geothermal power project on the provisioning of multiple ecosystem services [12]. Similarly to other comprehensive valuation studies, the process of estimating the economic value of impacts to the ecosystem services of geothermal areas is important, but will likely be challenging in three ways: (1) establishing the scientific links between project proposals and the economic value of changes in the quantity and quality of provisioned services; (2) ensuring that double counting of welfare benefits from specific ecosystem services does not occur; and (3) assembling sufficient resources in terms of funding, personnel and time to simultaneously conduct multiple economic valuation studies.

One area of particular intrigue in the debate about geothermal power concerns impacts to recreational amenity. Looking back at the attitudinal questions posed in this study, 62.18% of the sample either strongly or somewhat agreed with the notion that it was possible for geothermal areas to provide the same or similar levels of recreational benefits after a power plant was constructed. Other anecdotal evidence also supports the possibility that geothermal power projects do not necessarily have to undermine long-term recreational amenity and may even have the opposite effect. One example is Iceland's Blue Lagoon spa. Formed in 1976 by waste waters emanating from the Svartsengi Power Plant, the geothermal spa continues to attract a burgeoning clientele of tourists keen to relax in its waters [71]. Another case relates to the Hellisheiði Power Plant, where the facilities include a popular interactive exhibition for educating tourists and locals [72]. Further economic valuation studies are needed to investigate the impacts of geothermal power projects on recreational amenity. The Eldvörp field perhaps represents a suitable starting point for this research, as the further exploratory research by HS Orka will impact on a number of popular hiking trails in the area. Initially there is merit in applying the travel cost method to establish an estimate of the recreational value of the area in its current form. However, in order to understand the impacts to recreational amenity of a geothermal power project, it would be necessary for researchers to combine stated and revealed preference methods. Participants taking part in a travel cost study would need to be asked how their frequentation of the area might vary in the light of power project proposals, with the change in consumer surplus between the total studies equating to the social welfare implications associated with qualitative changes to recreational amenity.

Other valuable insights into the economic impact of geothermal power projects could be sought via an *a priori* approach. Rather than assuming that project proposals are a given and determining the economic value of environmental impacts relating to these, there may be the potential for economic information to influence design. Discrete choice modelling could be carried out to analyse economic preferences for different design parameters, such as the location of pipes, visibility of plant infrastructure, installation of scrubbing equipment to remove hydrogen sulphide emissions, and the extent of vegetative disturbance.

5. Conclusion

This paper used the CVM to estimate the economic value of preserving two high-temperature geothermal fields in Iceland, both likely to be developed in the near future. The methodology applied in this paper could be adopted to satisfy the OECD's repeated calls for Iceland to account for environmental impacts of power projects in cost-benefit analyses, which would potentially reduce the risk of sub-optimal decision-making.

Based on impact scenarios derived from Environmental Impact Assessments, which were based on design proposals for Eldvörp and Hverahlíð, the contingent valuation studies revealed estimated mean economic values of 8433 and 7122 ISK. Based on the affected population of Icelandic taxpayers, these equated to estimated total economic values of 2.11 and 1.78 billion ISK for Eldvörp and Hverahlíð respectively. These are not inconsiderable estimates, amounting to approximately 2% of the total lifetime construction costs of Iceland's largest geothermal plant, Hellisheiði. As such, they imply the need for further research focused on the economic value of the environmental costs associated with developing geothermal power projects in Iceland and beyond. In addition, their scale in itself provides an evidence base supporting the incorporation of utilitarian values of the environment into Icelandic decision-making processes.

The results from these studies considerably advance academic knowledge concerning preferences and willingness to pay for the preservation of geothermal areas, which, until this study, had been limited to the contingent valuation study by Thayer [4]. However, considerable further research is necessary to understand the economic impacts to specific ecosystem services associated with the development of geothermal environments, particularly connected to changes in recreational amenity and landscape aesthetics. In so doing, it would be possible to gain greater comprehension of impacts to the various components of total economic value, leading to understanding of why the environmental costs associated with developing one geothermal field – in this case Eldvörp – may be perceived to be greater than another. At this stage, until further knowledge is acquired of the economic value of preserved geothermal fields and their respective ecosystem services, it is recommended that the results from these studies are considered indicative and not used in any studies reliant on benefit transfer methodology.

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6. Paper V: The contingent valuation study of Heiðmörk, Iceland – willingness to pay for its preservation

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Research article

The contingent valuation study of Heiðmörk, Iceland – Willingness to pay for its preservation

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ABSTRACT

The decision-making and policy formation context in Iceland has been largely devoid of total economic valuations in cost-benefit assessments. Using an internet survey and applying the double bounded dichotomous choice methodology, this contingent valuation study sets out an estimate of the total economic value pertaining to Heiðmörk, a popular recreational area of urban open space located on the fringes of Reykjavík, Garðabær and Kópavogur. In so doing, this case study advances the practice of using non-market valuation techniques in the country. The welfare estimates provide evidence that Icelanders consider Heiðmörk to possess considerable total economic value, with taxpayers willing to pay a mean lump-sum tax in the range 17,039 to 24,790 ISK per payment to secure its preservation, equating to an estimated total economic value of between 5.87 and 35.47 billion ISK. In the light of possible competitive land management demands among Heiðmörk's three owners and many recreational users in the future, the establishment of these values and their potential use in cost-benefit assessments informs the debate concerning whether the area should be preserved or further developed to satisfy economic objectives. Additionally, a body of experimental evidence is formed suggesting that the increased duration of a fixed payment vehicle is associated with much higher total economic valuations compared to a one-year payment period.

1. Introduction

Economic valuations of environmental goods are a pre-requisite of socially optimal environmental policy (Mitchell and Carson, 1989; Hanley and Splash, 1993; Haab et al., 2013; Cook et al., 2016). The approval of development projects with significant environmental impacts implies that the economic costs of the affected environmental resources are less than the financial gains, but such decisions are frequently made without ever attempting to estimate monetarily the actual costs of the marginal losses. In Iceland, cost-benefit assessments have been undertaken without conducting total economic valuations to guide decision-making, meaning that the monetary value of socially desirable goods, such as recreational pursuits in preserved natural areas, has been ignored (Cook et al., 2016, 2017). This is despite heated debate in recent years concerning the trade-off between environmental goods and industrial development, as well as consistent calls by the OECD advising Iceland to begin accounting for the environment in the economic assessment of development projects (OECD, 1993; OECD, 2001; OECD, 2014). In the absence of total valuation accounting, decision-makers are potentially approving projects that may undermine social welfare.

The contingent valuation method (CVM) is a state-of-the-art survey-based technique that is consistent with economic welfare theory (Boyle, 2003) and has been applied across a variety of contexts to elicit monetary valuations of environmental resources (Stenger and Willinger, 1998; Broberg and Brännlund, 2008; Loomis and Keske, 2009; Brander and Koetse, 2011; Damigos et al., 2017). The approach has been used extensively as a basis for policy decisions, including but not limited to projects related to recreational value and the protection of open access resources, the health impacts of exposure to toxins, transport safety, groundwater usage, hunting and fishing permits in national parks, and biodiversity protection (Carson, 2012; Hanley et al., 2013). Particularly for

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resources such as urban open spaces, where multiple ecosystem services are often delivered simultaneously across several system components, the CVM's capacity to appropriate use (Bateman and Willis, 2001), option (Weisbrod, 1964; Hanemann, 1989a) and non-use (Krutilla, 1967; Carson et al., 1995; Hanley et al., 2013) value ensures that it has considerable merit as a stand-alone estimate of marginal changes total economic value (Cook et al., 2017). Furthermore, the public goods characteristics of urban open spaces exacerbate the importance of estimating their total economic value, enabling decision-makers to be more fully informed about their preservation merits (McConnell and Walls, 2005; Brander and Koetse, 2011; Dickinson and Hobbs, 2017). This need is especially acute when urban sprawl diminishes the availability of accessible open space on the fringe of conurbations (Maxwell, 1994; Faushold and Lilieholm, 1999).

Over the years, the literature on the CVM has included criticisms of the potential for its monetary valuations to be influenced by bias, including but not limited to information and eliciting effects, hypothetical, starting-point and strategic biases (Duffield and Patterson, 1991; Diamond and Hausman, 1994; Hausman, 2012). In addition, the literature has often explored the sensitivity of WTP to the scope of the project (Loomis, 1990; Carson, 1997, 2000; Nielsen and Kjær, 2011). A variety of explanations have been put forward for observations of the lack of sensitivity of WTP to the scope of projects, including flaws in the survey design leading to amenity misspecification bias (Carson and Mitchell, 1993), diminishing marginal values from successive units of protected areas (Rollins and Lyke, 1998), and income effects (Veisten et al., 2004). However, many of the perceived weaknesses of the CVM can be overcome provided the survey design is carefully conceived, especially with respect to the sampling procedures, realism of the scenario and a clearly defined scope, inclusion of appropriate validity checks, and the incentive compatibility and consequentiality of the chosen payment vehicle (Carson et al., 2001; Kling et al., 2012; Haab et al., 2013; Johnston et al., 2017).

One scope-related issue that has been largely overlooked in the literature concerns the sensitivity of willingness to pay (WTP) to the duration of a payment vehicle. Assuming no forms of bias influences the results, the estimated total economic value of a well-defined environmental good should not differ in response to payment vehicles of varying duration. Instead it has been reported that the total economic value of public goods can be considerably larger when the commitment involves multiple rather than one-off payments (Rowe et al., 1986; Carson et al., 1992; Kahneman and Knetsch, 1992). Thus, rather than one total economic valuation for the same good being formed, a wide range may be established, even when unconventionally high discount factors are applied (Kahneman and Knetsch, 1992). Based on the outcomes from the Rowe et al. (1986) study, Kahneman and Knetsch (1992) contend that such outcomes are caused by a temporal embedding of payments, whereby participants are entirely unable to discriminate between payments that vary in temporal inclusiveness. The study by Rowe et al. (1986) was based on willingness to pay (WTP) for a toxic waste treatment facility in British Columbia through either a one-time or five-year set of payments. The mean WTP for the one and five year responses were only $6 dollars apart, resulting in considerably higher total economic value associated with the longer payment duration, even when unconventionally high discount factors were applied. In contrast, Carson et al. (1992) found that WTP for scrubbing technology in an Ohio power plant was sensitive to some degree to a payment vehicle duration of either one or twenty years. However, the difference in total economic valuations was still consistent with discounting at very high rates of much more than 10% (Carson et al. (1992). The bank of evidence concerning the temporal embedding of payments in contingent valuation studies is currently very limited due to the small number of studies.

The three main aims of this paper concerning the case study of Heiðmörk – a popular but unprotected recreational area of urban open space on the edge of Reykjavík's capital area – are (1) to document in detail a methodologically robust application of the CVM in Iceland by eliciting a WTP estimate for Heiðmörk's preservation; (2) communicate results from an experiment concerning WTP responses to a payment vehicle of varying duration; and (3) enhance the growing literature concerning marginal changes to the total economic value of urban open spaces, in this case also an area with complicated management arrangements involving a number of stakeholders.

Section 2 of this paper begins by summarising the physical components of Heiðmörk, before providing a detailed review of this paper's methodology, including the survey design and mode of statistical analysis. Section 3 sets out the results from the study including the statistically significant predictor variables influencing WTP. Section 4 discusses the results and the possible explanations behind the range of welfare assessments formed by the three payment vehicle durations, implications of the outcomes with regards to cost-benefit assessments, and the likely wider relevance of the CVM in terms of future decision-making in Iceland.

2. Study site and survey methodology

2.1. Physical components of Heiðmörk

Heiðmörk is an urban open space of over 3000 hectares located to the south-east of Reykjavík, Iceland's capital city, and its neighbouring municipalities of Garðabær and Kópavogur. First given to the Reykjavík Forest Association in 1946, Heiðmörk was subsequently enlarged in 1957 to include land belonging to the Vífilsstaðir sanatorium and adjoining land from the Garðabær municipality (Marteinsson, 1975). Today, the Reykjavík Forest Association retains a daily supervisory role concerning its management. Land ownership is divided between the municipalities of Reykjavík and Garðabær, with Reykjavík Energy, a public company, in sole charge of its reservoirs. A map of Heiðmörk, which was provided to participants of the online contingent valuation survey, is in Fig. 1 below.

Replete with forests, lava fields, two lakes (Elliðavatn and Vífilstaðavatn), open areas, cycle paths, footpaths, rest areas, and camping facilities, Heiðmörk is the largest area of urban open space in the vicinity of Reykjavík and currently provides recreational benefits to over 500,000 visitors a year (Bell et al., 2009; Davíðsdóttir, 2010), a sizeable number compared to the current national population of a little over 328,000 individuals. The area provides diverse ecosystem services including drinking water, electricity from a small hydropower plant, recreational benefits, carbon sequestration, educational and cultural benefits, and habitat services for various fish and bird species (Davíðsdóttir, 2010). Approximately 89% of its area is classified as vegetated land, and the remaining areas are mainly lakes (8%) and gravel surfaces (3%) (Egilsson and Guðjónsson, 2006). Heiðmörk is located on the Trölladyngja volcanic system and it is surrounded by numerous lava beds and caves (Guðmundsson, 2001). Fissures and faulting of the volcanic system run through the area from north-east to south-west and visibly put their mark on the landscape, providing an ideal environment for the groundwater streams originating in the nearby mountains. Located in the northern part of Heiðmörk are remnants of pseudocraters, geological features that, as far as is known, can only be found in Iceland and on the planet Mars (Thordarson and Hoskuldsson, 2002).

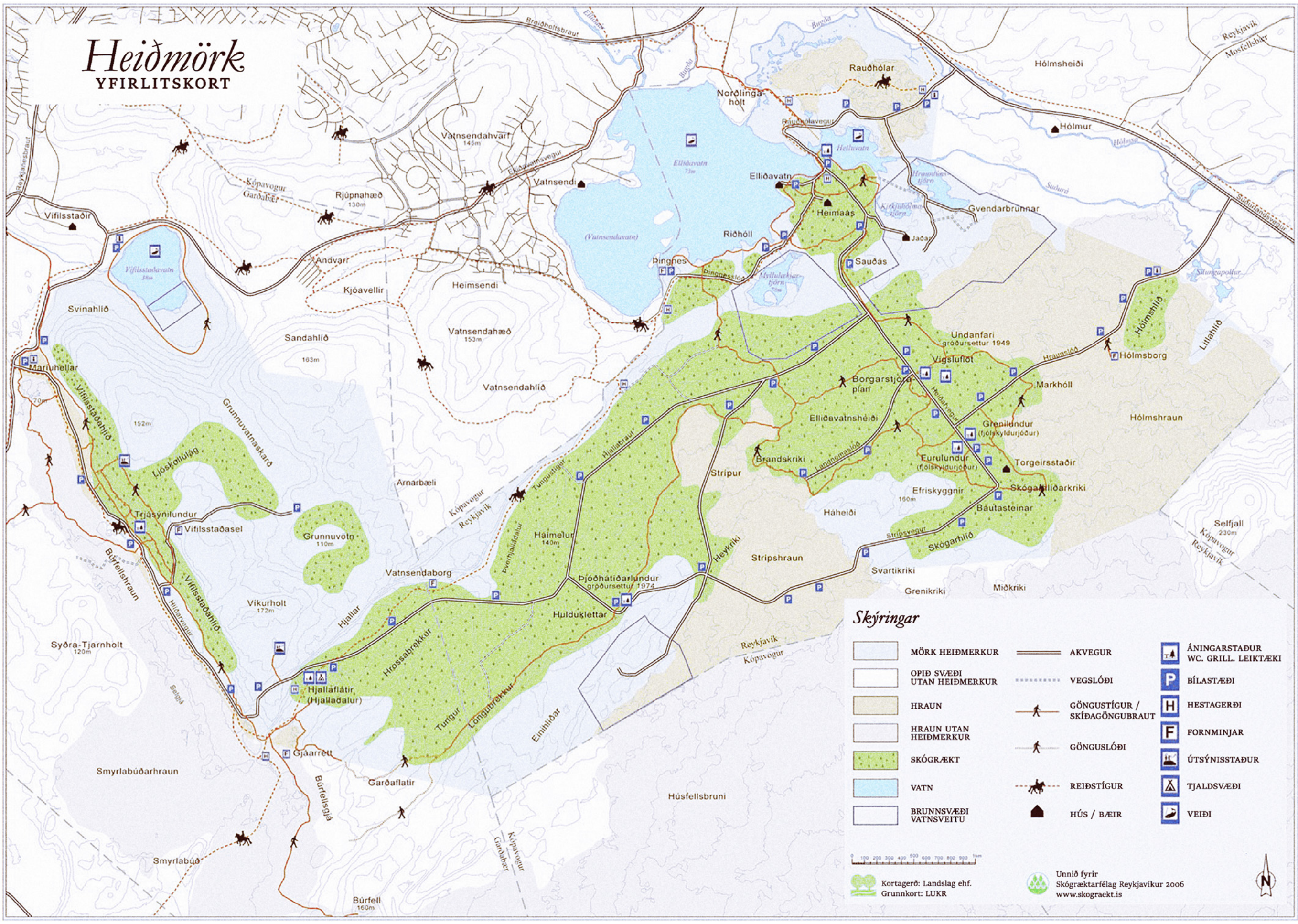

Fig. 1. Map of Heiðmörk.

2.2. Survey administration

Various instruments have been used to conduct contingent valuation surveys, including mail surveys, telephone surveys, face-to-face interviews, and mixtures of the aforementioned (Carson and Hanemann, 2005). Different survey instruments come with various pros and cons in terms of costs, biases and participation rates (Mitchell and Carson, 1989; Carson et al., 2001; Marta-Pedroso et al., 2007). Web-based surveys have been associated with some negative effects compared to face-to-face interviews, such as increased levels of “don't know” responses and the lack of any immediate opportunity for respondents to seek clarity about the questionnaire (Lindhjem and Navrud, 2011). However, although the National Oceanic and Atmospheric Administration (NOAA) panel advocated the use of face-to-face interviews (Arrow et al., 1993), for this study a web-based format was chosen for two main reasons. First, it was a cost-effective means of obtaining a large sample as 93.4% of the Icelandic population had access to the internet in 2010 (Statistics Iceland, 2013). Second, the format allowed for extensive randomisation, branching and split sampling, and was able to provide participants with visual aids, including the map in Fig. 1. Even though use of the internet to administer surveys is a fairly new approach in the CVM literature, evidence has been found in support of the method in terms of statistically insignificant differences in mean and median WTP compared to other survey instruments (Nielsen, 2011; Lindhjem and Navrud, 2011).

2.3. Survey design and structure

The contingent valuation component of the web survey was designed with the objective of being in accordance with the various best practice guidelines set out by Arrow et al. (1993), Carson (2000), Carson et al. (2001), Carson and Groves (2007), Kling et al. (2012), and Haab et al. (2013). Its aim was to minimise any possible biases and test if there was evidence of sensitivity to scope in terms of the duration of the payment vehicle. Neither the Rowe et al. (1986) nor Carson et al. (1992) evaluations concerning WTP and payment vehicle length were based on sample sizes of more than 500, which were then split between the respective payment durations. As far as the researchers are aware, this is the first study based on very large sub-sample sizes (each of more than 500 participants) to explore the sensitivity of WTP to various tax payment durations of either one, five or ten years.

The web survey was structured in the following manner: in the first section participants were asked three simple questions regarding their attitudes towards the environment and taxation in general. Next they were asked about their familiarity with Heiðmörk. If their answer to this question was ‘yes’, they were then asked if they had ever visited Heiðmörk, and based on that answer they either received questions about their use of the area or were moved on to the next part of the survey. Then a sub-sample of 1250 individuals from Reykjavík and Garðabær were presented with choice experiments (the results of these will form the subject of a separate publication) regarding their WTP for quality changes in specific recreational attributes of the site and validity checks were undertaken afterwards. All other participants moved immediately on to the contingent valuation scenario. Individuals who were against the preservation of Heiðmörk moved on to questions designed to sort the protestors from those with a pure preference against preservation. Participants with a WTP for preservation of the site were presented with double-bounded WTP questions and validity checks afterwards, which included a requirement to state how long they had perceived the tax payment duration to be. The final part of the survey, as is customary, was comprised of socio-economic questions in order to ascertain the factors influencing WTP. These questions were issued at the very end of the survey since they have the potential to stimulate a state of objection amongst participants (Carson et al., 2001).

The web-based survey format provided considerable opportunities and advantages in terms of design. As well as communicating a straight-forward, interactive and visually amenable presentation, participants were not able to browse through the survey and answer questions in the wrong order. The survey was interactive and branched to a considerable extent, so that participants did not have to respond to questions that were irrelevant to them based on their previous answers. To prevent ordering effects within each question, answer possibilities were always randomised, except where there was an inherent ordering in the answers. Participants had the option to answer nearly all of the questions with either *"I do not know"* or *"I do not want to answer"*, and were therefore never coerced into giving an answer that they would rather not provide. The exception to this concerned the 'yes/no' options that were available in the WTP elicitation process, bid questions that were only asked to participants with a willingness to preserve Heiðmörk. The easy-to-understand design of the survey allowed for quick completion and the number of questions ranged from 19 to 37, depending on participants' answers. In addition, the use of a web-based survey was particularly useful for randomising the tax payment durations in a manner which ensured that no participants were aware of this underlying process.

2.4. Survey implementation

The survey was implemented with the help of Capacent Gallup's Internet panel in June 2010. Participants in the panel, 15,000 in number at the time, are selected at random from the national registry to ensure they are representative of the Icelandic population and to prevent self-selection. Prior to implementation, the survey and its design were extensively tested. Web-based elements, such as the branching and randomisation of bids, were tested in a separate survey on the value of the Icelandic cow breed in 2009. The WTP scenario and certain elements of the survey were tested on two focus groups and in May 2010 the entire survey was pre-tested with a pilot study on 100 individuals. Based on the focus groups and experience from sampling users on-site, the affected population for the survey was considered to be the entire nation. Since the payment vehicle used to elicit WTP was an additional lump-sum tax, the affected population became all taxpayers in Iceland. A sample of 3900 18-75 year-old individuals was drawn from the Internet panel.

All individuals that were drawn into the sample received an email asking them to participate in a survey on socially important goods and services and public decision-making. The text was designed with the intent to increase the participation rate without causing self-selection bias. Therefore, the specific site of Heiðmörk was not mentioned in the email. The survey was open for two weeks and during that period those who had not participated within a few days of the initial email were sent a reminder asking them to participate. A total of 2656 individuals participated in the survey, equating to a response rate of 68%. This is akin to typical response rates for telephone surveys and above the level of participation found in most mail surveys, but a little lower than normal involvement rates when in-person interviews are carried out (Whitehead et al., 1993; Marta-Pedroso et al., 2007). The sample, with respect to the weighting, was found to be very comparable to the Icelandic population in terms of gender balance, age, marital status and disposable income distribution, with comparable proportions to those identified in the Icelandic Census for 2011, as shown in Table 1 (Statistics Iceland, 2014a).

2.5. Scenario description and payment vehicle

In contrast to normal opinion polls, contingent valuation surveys include a detailed description of a scenario that essentially constructs a hypothetical market for participants (Carson, 2000). However, it is vital that the hypothetical market is kept as real (Cummings and Taylor, 1998) and consequential (Carson and Groves, 2007) as possible to limit the effects of bias on welfare estimates. The survey provided participants with a detailed description about the current management and ownership of Heiðmörk, as well as many examples of the site's attributes. In addition, participants were carefully reminded about the fact that Heiðmörk is not protected in the legal sense, and thus there are no legislative barriers preventing future economic development, particularly adjacent to the roads Suðurlandsvegur and Reykjanesbraut. Furthermore, due to the absence of legal protection and split ownership of the site, participants were made conscious of potential land management conflicts between utilisation and preservation desires. In order to alleviate this problem, the description proposed that national legislation would be implemented to ensure that the area was preserved for the foreseeable future. However, due to the forgone future economic benefits suffered by the landowners, an additional annual lump-sum tax would be necessary to pay for Heiðmörk's preservation. The scope of the area to be preserved was clearly defined in the text as excluding the water catchment area, since this was already protected. As for the consequentiality of the legislation and tax payments, participants were told the decision would ultimately depend on the results of this survey.

Table 1
Sample and Icelandic population composition.

Criteria	Sample percentage	Population percentage
Gender		
Male	48	50
Female	52	50
Age		
18-25 years	15	16
26-35 years	20	19
36-45 years	15	17
6-55 years	18	17
56-65 years	15	15
66-75 years	10	9
76 years or older	7	7
Marital status		
Single	22	22
In a relationship	25	24
Married/cohabiting	45	46
Divorced/separated	7	6
Widow/widower	2	2
Disposable income		
250,000 ISK or lower	8	9
250,001–500,000 ISK	30	31
500,001–750,000 ISK	30	29
750,001–1,000,000 ISK	17	18
More than 1,000,000 ISK	13	13

The scenario was pre-tested on two focus groups and was widely accepted as being realistic and consequential. The focus groups revealed that people were generally unaware of the ownership of the area and its management. Moreover, it was a surprise to many that the area was not legally protected. Following the scenario description, participants were reminded about their budget constraint and asked whether they were for or against the preservation of Heiðmörk, much like the approach in referendum voting (Kling et al., 2012).

In recent years, considerable focus has been allocated to the overall valuation process, with due recognition that WTP estimates are strongly influenced by the procedures through which the resource is provided and how the payment is made (Cummings et al., 1986; Mitchell and Carson, 1989; Morrison et al., 2000). A realistic and neutral choice of payment vehicle can be incentive compatible (Mitchell and Carson, 1989; Carson, 1997; Carson et al., 2001; Grammatikopoulou and Olsen, 2013). In this study, the decision to impose an additional lump-sum tax, charged to all taxpayers aged over 18 years in Iceland irrespective of income, was made due to its incentive compatibility compared to voluntary arrangements. Its design was similar to other lump-sum taxes in Iceland, such as the annual fixed levy towards the state television and radio production. This is currently a tax of 18,800 ISK per year and is only required to be paid by individuals of at least 18 years of age with taxable income (Invest in Iceland, 2014). Assuming that participants believed in the survey's scenario, the design of the tax and knowledge that it would be levied irrespective of income minimised the risk of strategic bias influencing the welfare estimates. In recent years there has been discussion concerning whether WTP should be aggregated across the affected population on an individual or household basis (Lindhjem and Navrud, 2009). Given the characteristics of the proposed tax, which was to be levied on all individuals in Iceland with taxable income, the affected population was determined to be all taxpayers in Iceland.

2.6. Elicitation of WTP

There are many different ways of eliciting WTP estimates using contingent valuation surveys. A variety of methods have been advocated in previous studies: open-ended questions (Bateman et al., 1995), payment cards (Olsen and Donaldson, 1998), dichotomous choice (single, one and a half, or double bounded) (Arrow et al., 1993; Cooper et al., 2002; Afroz and Masud, 2011; Cook et al., 2018)), iterative bidding games (Van Minh et al., 2013), and referendums (Dutta et al., 2007).

Dichotomous choice has proven to be a very widely adopted elicitation formation, mainly due to its simplicity of use in data collection (Antony and Rao, 2010) and statistical efficiency compared to the alternatives (Hanemann et al., 1991). This study adopted the double bounded version of the dichotomous choice model, a method that adds a second binary question based on the answer to the first. Thus, for all individuals with a WTP for the preservation of Heiðmörk, if the answer to the first question was 'no' then the second question offered a lower amount; if the answer to the first question was 'yes' then a higher amount was asked (Hanemann et al., 1991). Hanemann et al. (1991) and Kanninen (1995) demonstrated that the double bounded dichotomous choice approach is asymptotically more efficient than the single bound version.

When using the double bounded elicitation format, Cameron and Quiggin (1994) contend that as the second bid depends on the first bid, the two bid levels are dependent, leading to the first bid 'anchoring' WTP. The general explanation for 'anchoring' is that the first bid value provides participants with the psychological impression that the quantity to be estimated could be near this value (Green et al., 1998). In this study, efforts to increase the accuracy of the WTP distribution across the survey sample as a whole were undertaken by randomly varying the bid amounts, helping to reduce the possible influence of starting-point bias (Veronesi et al., 2011).

The first and second bid vectors were *designed* according to the following list of randomised possibilities, with the range of second vectors conditional on either the acceptance or rejection of the first bid: (First bid vectors) 5,000, 10,000, 15,000, 20,000, and 25,000 ISK; (Second bid vectors) 2,000, 8,000, 12,000, 20,000, 28,000, and 45,000 ISK. The first bid offers were randomly distributed, resulting in very equal sub-sample sizes for each WTP value: 5000 ISK (n = 321, 19.96%); 10,000 ISK (n = 330, 20.52%); 15,000 ISK (n = 306, 19.03%); 20,000 ISK (n = 313, 19.47%); and 25,000 ISK (n = 338, 21,02%).

Assuming an individual expressed a preference for the preservation of Heiðmörk, and depending on their responses to the two binary questions, their true WTP (y_i) lies somewhere in one of four possible ranges for $L_i \leq y_i \leq U_i$, where L_i and U_i represent the lower and upper limits. The response probability of the four intervals is as follows:

$$P(YY) = P(t_2 \leq y_i \ \leq \infty) \tag{1}$$

$$P(YN) = P(t_1 \leq y_i \leq t_2) \tag{2}$$

$$P(NY) = P(t_2 \leq y_i \leq t_1) \tag{3}$$

$$P(NN) = P(0 \leq y_i \leq t_2) \tag{4}$$

where: y_i = true WTP, t_1 = first bid. t_2 = second bid, YY = (yes, yes) response, YN = (yes, no) response, NY = (no, yes) response, NN = (no, no) response.

2.7. Statistical modelling of the results

Methods of analysis such as the logit or Probit models are inappropriate as they would rank WTP according to an ordinal model, ignoring the interval's lower and upper values. Instead, as the double bound dichotomous choice model delivers an estimated WTP for each participant within one of four possible ranges, it is appropriate to apply interval regression, a more general version of the Tobit model (Cameron and Huppert, 1989; Caudill and Long, 2010; Lu and Shon, 2012). The model estimates the probability that the latent variable, WTP, exceeds the lower limit of the interval but is less than the upper threshold.

Let the model be represented by:

$$y_i = x_i\,\beta + \varepsilon_i \tag{5}$$

where: y_i = the continuous, unobserved and underlying latent variable of WTP, x_i = the vector of predictor variables associated with respondents, β = the vector of coefficients on WTP to be evaluated, ε_i = a random error component of unobserved factors; $\varepsilon \sim N(0, \sigma^2)$

Following the approach of Cameron and Huppert (1989), interval regression was applied to the respective ranges for y_i expressed in equations (1)–(4). In accordance with Hanemann (1984), the upper bid values for (yes, yes) responses were not truncated, as a 'yes' answer to the second bid is not indicative of a maximum WTP, but rather a lower bound for WTP of that value.

The maximum likelihood equations for the respective ranges are written as follows:

$$L_i\ (\mu|t) = P(\mu + \varepsilon_i > t_2)^{YY} \tag{6}$$

$$L_i(\mu|t) = P(t_2 - \mu > \varepsilon_i > t_1 - \mu)^{YN} \tag{7}$$

$$L_i(\mu|t) = P(t_1 - \mu > \varepsilon_i > t_2 - \mu)^{NY} \tag{8}$$

$$L_i\ (\mu|t) = P(\mu + \varepsilon_i < t_2)^{NN} \tag{9}$$

where: L_i = the maximum likelihood of a WTP outcome, μ = mean, ε_i = a random error component, t_1 = first bid, t_2 = second bid, YY = (yes, yes) bid responses, YN = (yes, no) bid responses, NY = (no, yes) bid responses, NN = (no, no) bid responses.

This study adhered to Hanemann's (1989b) recommendation that the integration should not be extended to include negative WTP values, since WTP studies provide very poor approximations of negative WTP or willingness to accept (WTA) compensation. Instead, these participants, in line with the approach advised by Hanemann (1984, 1989b), and Haab and McConnell (1998), were allocated a WTP of zero on the basis of a genuine indifference between the preservation and development of Heiðmörk, leading to a zero-inflated spike model (Kriström, 1997; Nahuelhual-Muñoz et al., 2004). In theory, some of these participants might have a negative WTP for the preservation of Heiðmörk, however, this is only likely to arise due to a misperception of the good or context (Loomis and Ekstrand, 1998).

3. Results

3.1. Preferences for and against the preservation of Heiðmörk

Following the survey's scenario description, each of the 2656 survey participants was asked to state whether they had a preference for or against the preservation of Heiðmörk. A total of 471 participants failed to state their preferences for or against preservation, or did not provide important socio-demographic details in the final part of the survey, and thus their responses are omitted from the results, leaving 2185 remaining observations. Their omission is important in order to accurately reflect the proportion of participants who were against the preservation of Heiðmörk, and thus the impact of these participants with genuinely zero WTP on the mean and total WTP. Participants who were not in favour of preservation were asked a follow up question to determine whether they had a genuine preference against preservation or were a protest voter – the latter were individuals who expressed a preference against preservation, but also revealed themselves to be fundamentally against paying higher taxes and thus potentially concealing their true preferences. Table 2 describes the total number and proportion of the responses. A total of 1608 individuals expressed a preference to preserve Heiðmörk, equal to 73.59% of the total number who provided a complete response. Only these individuals were then invited to take part in the bidding process and express their WTP a lump-sum tax for Heiðmörk's preservation. All protest voters who were against the preservation of Heiðmörk were dropped from the results on the basis that their stated preferences were not necessarily indicative of 'true' values.

3.2. Survey and bid elicitation responses

Based on the 1608 observations expressing a preference for the preservation of Heiðmörk, Table 3 identifies the percentages of those who accepted or rejected the first bid, and the proportion of the sample proceeding to either accept or reject the second bid. It can be seen that 60.76% of participants in favour of conserving Heiðmörk answered yes to the first bid, but only 25.37% of all participants accepted the second, higher bid. A proportion of 39.24% rejected the first bid, and 23.07% of the whole sample responded 'no, no' to both binary questions.

Each of the 371 participants who rejected the first and second bid offers was asked to provide a reason in order to determine whether their negative responses derived from a disposal income constraint or a more fundamental objection to the payment vehicle. A total of 184 of the 371 participants (49.60%) answering 'no, no' to the two binary questions were identified as being additional protest voters against the imposition of the tax. However, unlike the 469 participants who had earlier been identified as protest voters via the question ascertaining their preferences against preservation, the observations pertaining to this group were retained in the subsequent WTP analysis as they had articulated a clear preference in favour of preservation.

The answers to the two binary questions and the random nature of the vectors assigned to participants led to the creation of 38 separate WTP intervals applicable to participants, every one falling within one of the four possible ranges described earlier in equations (1)–(4). Based upon this data, it was deduced that the array of WTP estimates were more closely assimilative with the normal rather than log-normal distribution.

3.3. Summary of predictor information and socio-demographic characteristics

Table 4 outlines the descriptive statistics for the regression model's predictor variables, grouped according to whether participants were for or against preservation. For the socio-demographic variables, only the predictor variables found to be statistically significant in the subsequent interval regression models are reported. The upper bound for WTP excludes the 408 observations who answered 'yes, yes' to the two binary questions in the elicitation process, as well as 3 individuals with a preference for conservation who failed to confirm whether they were a user of Heiðmörk or not. Non-applicable entries are marked with a dash (–) symbol. Dummy variables explored the influence of being an existing or future user of Heiðmörk on WTP, residence, the actual and perceived tax payment durations, and the effect of the preceding choice experiment on WTP for observations from Reykjavík and Garðabær. A further dummy variable was run as a test of scope evaluation, with individuals asked to state 'yes', 'no' or 'don't know' to the question of whether the tax was also going to contribute to the preservation of the privately owned reservoirs within Heiðmörk, which was not

Table 2
Preferences for and against the preservation of Heiðmörk.

Response	Frequency	Percentage (%)	Cumulative Percentage (%)
For preservation	1608	73.59	73.59
Against preservation	108	4.94	78.53
Protest voters	469	21.46	100.00
	2185	**100.00**	

Table 3
Summary of first and second bid responses (percentages of total in brackets).

		Second bid		
		Yes	No	Total
First bid	Yes	408 (25.37)	569 (35.39)	977 (60.76)
	No	260 (16.17)	371 (23.07)	631 (39.24)
	Total	668 (41.54)	940 (58.46)	1608 (100.00)

Table 4
Descriptive statistics of predictor variables.

Variable	Description	Preference for preservation		Preference against preservation	
		Mean	Standard deviation	Mean	Standard deviation
WTP					
Lower bound	Lower bound of WTP (ISK)	12,884.95	13,420.34	–	–
Upper bound	Upper bound of WTP (ISK)	23,621.67	14,175.07	–	–
Socio-demographic					
Children	Number of children under the age of 18 in the household	0.93	1.10	0.99	1.11
Gross monthly income					
Income 1	Dummy for 0–250,000 ISK	0.07	0.25	0.06	0.23
Income 2	Dummy for 250,001–500,000 ISK	0.26	0.44	0.26	0.44
Income 3	Dummy for 500,001–750,000 ISK	0.26	0.44	0.24	0.43
Income 4	Dummy for 750,001–1,000,000 ISK	0.15	0.36	0.19	0.40
Income 5	Dummy for more than 1,000,000 ISK	0.11	0.31	0.14	0.35
Income missing	Dummy for missing income	0.15	0.36	0.11	0.32
Residence					
Reykjavík	1 for residency, 0 for not	0.59	0.49	0.43	0.50
Garðabær	1 for residency, 0 for not	0.09	0.29	0.07	0.26
Everywhere else	1 for residency, 0 for not	0.32	0.47	0.50	0.50
Actual payment vehicle duration					
One year	1 for duration of 1 year, 0 for not	0.32	0.47	–	–
Five years	1 for duration of 5 years, 0 for not	0.36	0.48	–	–
Ten years	1 for duration of 10 years, 0 for not	0.32	0.47	–	–
Perceived payment vehicle duration					
One year	1 for perception of 1 year, 0 for not	0.22	0.41	–	–
Five years	1 for perception of 5 years, 0 for not	0.30	0.46	–	–
Ten years	1 for perception of 10 years, 0 for not	0.22	0.41	–	–
Twenty years	1 for perception of 20 years, 0 for not	0.03	0.17	–	–
Forever	1 for perception of forever, 0 for not	0.05	0.23	–	–
Answer missing	1 for answer missing, 0 for not	0.18	0.39	–	–
Other dummies					
User	1 for user, 0 for not	0.97	0.18	0.88	0.33
Choice experiments	1 for belonging to the sub-sample, 0 for not	0.37	0.48	0.31	0.46

the case as had been explained in the scenario description. It was found that the variable was not significant at the 10% level, and therefore these results are not discussed any further in this paper.

In terms of the limited number of statistically significant socio-demographic variables, there were only very small differences between the participants who were for or against the preservation of Heiðmörk. The mean number of children living in the households of participants with preference for preservation was 0.06 lower than those who were against, and in both cases the mean number was less than 1. Across both groups, the most common gross monthly individual income was either 250,000–500,000 ISK or 500,001–750,000 ISK, with over half of the participants falling within one of these two brackets. Proportionally, 3% more of the participants against preservation had the highest possible declaration of gross monthly income of more than 1,000,000 ISK per month.

The overwhelming majority (97%) of participants with a preference for preservation were users of the Heiðmörk resource, while this was the case for 88% of the participants against preservation. Of those with a preference for preservation, 27 participants asserted that they had neither visited Heiðmörk in the past nor intended to in the future, and therefore their value for Heiðmörk was an existence value. Compared to the remaining 1581 observations in the sub-sample, this very small group had similar socio-demographic characteristics, yet their WTP was demonstrably lower, with mean lower and upper intervals of 4607 ISK and 13,125 ISK respectively, some 8278 ISK and 10,497 ISK lower than the group as a whole. Note that the ISK: US $ and ISK: € exchange rates in 2010 were 1: 0.0081 and 1: 0.0063 respectively.

More obvious differences in the two groups are apparent in terms of residency. In comparison to those participants against preservation, 16% and 2% more lived in Reykjavík or Garðabær respectively, the two municipalities with ownership of Heiðmörk. Proportionally 18% more of the group against preservation lived outside of Reykjavík and Garðabær. At the same time, 6% more of the participants with a preference for preservation received the choice experiment part of the web-survey, but this outcome was influenced by the fact that only participants from the municipalities with ownership of Heiðmörk had received choice experiments.

Due to the randomised nature of the process, very similar proportions of the participants with preference for preservation were allocated tax payment durations of either one-year (32%), five years (36%), or ten years (32%). Responses to the validity tests concerning the perception of the tax payment duration were less predictable, with 26% of the group either not answering or stating the 'false' durations of twenty years and forever. In total, 996 (62%) of the 1608 observations with a preference for preservation answered this validation question correctly, 20% answered incorrectly, and a further 18% did not provide any answer.

3.4. Results from the interval regression models

The results from the interval regression analysis are shown in Table 5. This section outlines the results from two distinct models, based on the following:

(1) Participants with WTP for the preservation of Heiðmörk based on the actual duration of the payment vehicle as per the survey;
(2) Participants with WTP for the preservation of Heiðmörk based on their perceived duration of the payment vehicle.

Via an iterative process, statistically insignificant predictor variables were removed from both models until the point that the best

Table 5
Interval regression results.

Variable	Model 1 (n = 1605)	Model 2 (n = 1605)
Socio-demographic		
Children	−1067.42***	−1139.92***
	(380.96)	(382.41)
Gross monthly income		
Income 1	1409.02	1087.38
	(1839.33)	(1846.65)
Income 2	4246.47***	3926.05***
	(1282.52)	(1287.31)
Income 3	4843.62***	4264.95***
	(1294.64)	(1300.79)
Income 4	2873.72**	2581.07*
	(1449.29)	(1461.27)
Income 5	7804.28***	7181.82***
	(1631.50)	(1642.51)
Residence		
Reykjavík	4766.82***	4137.89***
	(1058.19)	(1063.64)
Garðabær	4787.03***	3996.60**
	(1629.77)	(1638.92)
Actual payment vehicle duration		
Five years	−8110.77***	–
	(991.35)	
Ten years	−8464.72***	–
	(1024.76)	
Perceived payment vehicle duration		
One year	–	–
Five years	–	4137.36***
		(1193.36)
Ten years	–	3287.54***
		(1267.29)
Twenty years	–	2264.10
		(2489.70)
Forever	–	8904.45***
		(2030.07)
Other dummies		
User	8084.43***	8887.97***
	(2276.49)	(2290.13)
Choice experiments	−2463.58**	−2259.54**
	(993.39)	(999.17)
Constant	14,498.76***	4187.17*
	(2401.35)	(2507.67)
Σ	14,705.54	14,772.94
	(328.40)	(329.77)
Log-likelihood	−2229.95	−2237.39
AIC	4487.90	4508.78
BIC	4563.23	4600.25

*** indicates significance at the 1% level, ** significance at the 5% level, and * significance at the 10% level; standard errors are in parentheses.

fit was established. Where variables are irrelevant, such as actual payment vehicle duration entries for model 2, these are marked with a dash (–). Insignificant dummy variables for income were retained as the income variable as a whole was significant at the 5% level of probability. The predictor variables for the one-year tax payment and residing 'everywhere else' are not reported in Table 5. This is because these are dummy variables for the same phenomenon captured by the other dummy variables for the tax payment durations and residence, thus leading to near perfect multicollinearity (Mansfield and Helms, 1982; Kutner et al., 2004). The observations for models 1 and 2 exclude 3 participants who expressed a preference for preservation but did not provide a response to the question of whether they were a user of Heiðmörk.

3.4.1. Results from interval regression model 1

The results show that having a greater number of children led to lower WTP by the amount of 1067 ISK per child. Given the increased costs associated with bringing up more children, this suggests that participants were taking into account their budget constraint during the bidding process.

Although not all of the dummy variables for gross monthly income were statistically significant, overall the variable was significant at the 5% level of probability, and three income brackets were significant at the 1% level of probability. Compared to participants with gross monthly income of less than 250,000 ISK, those with gross monthly income of 250,001–500,000 ISK and 500,001–750,000 ISK typically expressed a WTP of some 2837 ISK and 3435 ISK more respectively. Participants with gross monthly income of more than 1,000,000 ISK had WTP of 6395 ISK greater than the group with less than 250,000 ISK, and this dummy variable was significant at the 1% level of probability. However, an increased income did not necessarily equate to ever-increasing WTP, as participants with gross monthly income of between 750,001 and 1,000,000 ISK were only willing to pay 1465 ISK more than the group with less than 250,000 ISK, all other factors being equal.

A participant's residence was a significant factor influencing their WTP at the 1% level of probability. Individuals residing in the two municipalities of Reykjavík and Garðabær with ownership of Heiðmörk offered 4767 ISK and 4453.50 ISK more than individuals living anywhere else, all other factors being equal. WTP for the preservation of Heiðmörk therefore appears to be strongly associated with a tendency to be a user of the area due to the close proximity of their home. Indeed, 100.00% and 99.57% of participants with a preference for preservation and living in Garðabær and Reykjavík stated that they were users of Heiðmörk. The dummy variable for being a user of Heiðmörk was significant at the 1% level of probability and associated with an 8084 ISK increase in WTP. In contrast, it is apparent that the preceding contingent choice experiments issued to 589 of the residents from Garðabær and Reykjavík was associated with lower WTP of 2464 ISK. The reasons for this are not certain, although it is possible that these participants incorrectly believed that they were paying for the contingent choice outcomes *and* preservation of Heiðmörk, thus imposing even greater strain on their disposable income.

The length of the tax payments had a negative impact on WTP compared to the one year lump-sum scenario, although the reductions of −8111 ISK and −8465 ISK for the five and ten-year payment streams respectively are very small considering that participants are receiving the same environmental good irrespective of the number of payments. The possible explanations and implications of these outcomes are explored in more detail in the following section regarding the results for total WTP.

3.4.2. Results from interval regression model 2

In model 2, very similar outcomes to model 1 are derived in terms of the predictor variables that are found to be statistically significant and the size of their coefficients, although in comparison the latter are a little lower for those living in Reykjavík or Garðabær and the constant is only significant at the 10% rather than 1% level of probability. The stand-out feature from the model concerns the 86 participants who formed the erroneous perception that the tax payment duration is forever, a predictor variable found to be influential at the 1% significance level. All other factors being equal, these participants tended to have a higher WTP than all other perceived durations, except the one-year payment. This may suggest that these individuals generally believed that Heiðmörk would be preserved forever if the tax was levied forever, thus resulting in the form of likelihood bias discussed by Carson et al. (1992). The perception is likely to have stemmed from a misunderstanding of the wording in the survey's scenario, which had asserted that the tax payments would lead to the passing of national legislation to protect the area from future development in perpetuity, not that payments would be required forever.

3.5. Individual and total WTP estimates

Building on the results shown for model 1 in Table 5, the conditional WTP for each participant was predicted based on the expected payment lying in one of the four intervals expressed by:

$$y_i = E(y_i | L_i < y_i < U_i) \tag{10}$$

Estimating the mean WTP for each of the tax payment durations based on these outcomes would lead to a residency bias due to oversampling of participants from Reykjavík and Garðabær. This had occurred due to the need to secure a sample of sufficient size as a basis for the choice experiments. In order to correct this, for each of the tax payment durations the mean WTP for participants from Reykjavík, Garðabær and everywhere else was aggregated following weighting by the proportion of the national population from these areas, which in 2010 was 38.27%, 3.35%, and 58.38% respectively (Statistics Iceland, 2014b). Next, to account for the model's spike at zero for participants with a preference against preservation, the residency-adjusted mean values for the respective tax payment durations were adjusted downwards by the proportion of 4.94%.

Confidence intervals for mean and aggregate WTP were calculated based on the normal distribution given known variance of the population, as follows:

$$WTP - \frac{\frac{z\alpha\sigma}{2}}{\sqrt{n}} < \mu < WTP + \frac{\frac{z\alpha\sigma}{2}}{\sqrt{n}} \tag{11}$$

3.5.1. WTP – outcomes from model 1

Tables 6 and 7 set out the mean WTP per payment for each of the tax payment durations and aggregated values based on the population of 236,948 Icelandic taxpayers in 2010 (Statistics Iceland, 2014b). It is assumed that the first tax payment occurs in time period t_0, with the final payment of the ten year lump-sum tax occurring in t_9. On this basis, the aggregated value for the one-year tax is not discounted, whereas the five and ten-year estimates are by selected discount factors ranging from 3 to 20%.

Based upon actual participant responses to the three payment vehicle durations, model 1 provides a range estimate of mean per payment and total WTP for the preservation of Heiðmörk. As Tables 6 and 7 identify, estimated mean per payment WTP is between 17,039 and 24,790 ISK, while total WTP is between 5.87 and 35.47 billion ISK. The extent of the range for total WTP depends greatly on the choice of discount factor, with lower factors leading to the greatest difference in the bounds. Economic welfare theory would dictate that the three welfare estimates should be broadly similar, given that each sub-sample is equally representative of the Icelandic population of taxpayers, yet even the choice of an unconventionally high discount factor of 20% results in a difference of 14.44 billion ISK between the one and ten year estimates of total WTP.

3.5.2. WTP – outcomes from model 2

Mean per payment and aggregated WTP values were estimated using model 2 to evaluate outcomes based on the perceived duration of the tax payment vehicle. Table 8 sets out the mean WTP for each of the possible tax payment duration choices in the survey; 295 participants failed to provide an answer concerning their perception, and therefore the total number of observations in model 2 is 1310. Table 9 outlines the respective estimates for aggregate WTP using the same range of discount factors as per the analysis for model 1.

Although model 2 (n = 1310) is based on a more limited dataset than model 1 (n = 1605) due to the non-responses concerning the perception of the tax payment duration, Tables 8 and 9 identify that for participants stating a payment duration perception of either one, five or ten years, the mean per payment WTP was in the range 18,277 to 24,900 ISK and total WTP was between 5.90 and 38.05 billion ISK. Thus, assuming the lowest discount factor of 3% evaluated in this study and ignoring the twenty year and forever durations, the range for total WTP established by model 2 is some 2.55 billion ISK greater than model 1. In addition, factoring in the observations pertaining to the twenty year (n = 47) and forever (n = 86) tax payment durations leads to a considerably wider range for total WTP (from 5.90 to 186.69 billion ISK), again greatest when the lowest modelled discount factor is applied. The choice of discount factor greatly influences the size of the range in estimated total WTP – Table 9 identifies that a 20% factor results in a range equal to 22.10 billion ISK between the one year and forever welfare estimates, some 158.69 billion ISK less than the 180.79 billion ISK span obtained using a 3% rate.

4. Discussion

4.1. Mean and total WTP estimates

Based on model 1, the results for individual and total WTP in Tables 6 and 7 communicate a range of welfare estimates for the preservation of Heiðmörk, with mean WTP per payment in the band 17,039 to 24,790 ISK and, assuming the lowest modelled discount rate of 3% and a population of 236,948 Icelandic taxpayers, an aggregate economic value of between 5.87 and 35.47 billion ISK. To place these figures into some sort of context, in comparison to Iceland's GDP of approximately 1600 billion ISK in 2010, the range in total WTP is equivalent to between 0.36% and 2.22% of national economic output. In the light of the historical expansion of Reykjavík's urban fringe towards Heiðmörk, these values should help to better inform decision-making in the future, particularly in terms of whether to preserve the urban open space for recreational pursuits or favour further economic development.

As the mean values set out in Table 6 relate to different payment durations, they are useful for communicating implications about the character of participant preferences when faced with a payment vehicle of an extended duration. On the basis that participants make their fifth tax payment in period t_4 and tenth in t_9, unconventionally high discount factors of 228.58% and 219.82% must be applied to the five and ten-year duration means to render the aggregated stream of payments equivalent to the one-year welfare estimate. The disparity in outcomes is perhaps observed even more clearly when the mean WTP outcomes are aggregated

Table 6
Estimated mean WTP based on model 1.

	Mean WTP per payment (ISK)	Standard deviation (ISK)	95% confidence interval (ISK)	
One year tax	24,790	11,599	24,304	25,276
Five year tax	17,291	9813	16,879	17,702
Ten year tax	17,039	9410	16,644	17,433

Table 7
Aggregate WTP based on model 1.

Discount factor	Aggregate WTP (billion ISK)	Standard deviation (billion ISK)	95% confidence level (billion ISK)	
One year lump sum tax				
Not discounted	5.87	2.75	5.76	5.99
Five year lump sum tax				
3%	19.33	10.97	18.87	19.79
5%	18.62	10.57	18.18	19.07
10%	17.08	9.70	16.68	17.49
15%	15.79	8.96	15.42	16.17
20%	14.70	8.34	14.35	15.05
Ten year lump sum tax				
3%	35.47	19.59	34.65	36.29
5%	32.73	18.08	31.98	33.49
10%	27.29	15.07	26.66	27.92
15%	23.30	12.87	22.76	23.84
20%	20.31	11.22	19.84	20.78

Table 8
Estimated mean WTP based on model 2.

	Mean WTP per payment (ISK)	Standard deviation (ISK)	95% confidence interval (ISK)	
Answered one year tax	24,900	11,600	24,413	25,386
Answered five year tax	18,845	10,022	18,425	19,265
Answered ten year tax	18,277	10,090	17,854	18,700
Answered twenty year tax	18,838	10,096	18,415	19,261
Answered forever	23,637	11,813	23,141	24,132

Table 9
Aggregate WTP based on model 2.

Discount factor	Aggregate WTP (billion ISK)	Standard deviation (billion ISK)	95% confidence level (billion ISK)	
Answered one year tax				
Not discounted	5.90	2.75	5.78	6.02
Answered five year tax				
3%	21.06	11.20	20.59	21.53
5%	20.30	10.79	19.85	20.75
10%	18.62	9.90	18.20	19.03
15%	17.21	9.15	16.83	17.60
20%	16.02	8.52	15.67	16.38
Answered ten year tax				
3%	38.05	21.01	37.17	38.93
5%	35.11	19.38	34.30	35.92
10%	29.27	16.16	28.59	29.95
15%	24.99	13.80	24.42	25.57
20%	21.79	12.03	21.28	22.29
Answered twenty year tax				
3%	68.40	36.66	66.86	69.94
5%	58.41	31.30	57.10	59.72
10%	41.80	22.40	40.86	42.74
15%	32.13	17.22	31.41	32.85
20%	26.08	13.98	25.50	26.67
Answered forever				
3%	186.69	93.31	182.78	190.60
5%	112.01	55.98	109.67	114.36
10%	56.01	27.99	54.83	57.18
15%	37.34	18.66	36.56	38.12
20%	28.00	14.00	27.42	28.59

using the population of Icelandic taxpayers, as shown in Table 6. Here, irrespective of the discount factor used, from a low rate of 3% to a very unusually high choice of 20%, the difference in the total economic value between the durations is considerable – given that the lowest rate of 3% results in the greatest range of outcomes, the estimated total economic value of Heiðmörk is between 5.87 and 35.47 billion ISK. There are various explanations as to why the disparity may be so large. In the first instance, this outcome runs somewhat contrary to the contention by Kahneman and Knetsch (1992) that survey participants are *entirely* unable to discriminate between one-year and longer streams of payments when forming their WTP estimate. Although there is only a 252 ISK (1.46%) difference between mean per payment WTP for the five and ten year payments, the divide between the one year and five year durations is 7499 ISK (30.25%). Thus this outcome is certainly suggestive of a possible temporal embedding of payments in terms of a comparison between the five and ten year durations, but the effect is considerably less clear-cut with regards to the one-time and five year long payments. Yet, a temporal embedding of payments is only one possible explanation for these results. Given that the environmental good in question – preservation of an urban open space – is not a fixed, technical installation that is unlikely to be removed, it would appear that payment durations of greater than one year are associated with the form of likelihood bias discussed by Carson et al. (1992). This effect stems from the belief on the part of participants that longer payment streams are more likely to result in the receipt of a particular good, as government's very rarely set one-off taxes. Feedback responses from participants receiving the one-year tax payment option often expressed the opinion that the duration lacked plausibility; the five and ten year sub-samples voiced this contention less frequently. Therefore, although additional lump-sum taxes had a precedent in Iceland in the form of the state TV levy, the duration of the one-year payment was perhaps the least likely of the three lengths to promote incentive compatibility and, if this was the case, the value of 5.87 billion ISK likely represents a low-estimate of the environmental costs of developing Heiðmörk, given the scenario of development presented to the survey participants.

Although the passing of national preservation legislation may have appeared an overwhelming barrier to the future economic development of Heiðmörk, equally some participants may have found this premise to be hypothetical. Legislation can be changed in the future. It is possible to speculate that participants were only willing to believe that national legislation would be maintained if they made a tax contribution over a longer period. If so, then the likelihood bias relative to the one-year payment scenario may have resulted in upward pressure on WTP. The outcomes from model 2 are certainly indicative of such an effect. Participants who perceived a tax payment duration of either twenty years or forever had mean WTP of 18,838 and 23,637 ISK per payment respectively. The former value was only 7 ISK per payment lower than the amount associated with the perceived five-year tax payment duration, however, the latter was 20.27% to 22.68% higher than all of the other mean perceived payment durations, apart from the one-year value. Aggregate WTP based on these two perceived durations were extremely high, at 186.69 billion ISK in the case of payments required forever. Results such as these strongly suggest a behavioural tendency for participants to consider the preservation of an open access resource to be more likely if they pay more over an extended period of time.

In the light of the outcomes, which have stimulated speculative analysis as to their cause, it is not possible to determine with certainty the least or most valid welfare estimate, or indeed whether outcomes have been affected by the temporal embedding of payments or likelihood bias afflictions. Moreover, should the range of outcomes be based on aggregations formed from the actual payment durations or their perceived lengths? Overall, given that model 1 is not undermined by the presence of missing data entries, it seems reasonable to prefer these results. Given the choice of discount rates analysed in this paper, the marginal change in the estimated total economic value of Heiðmörk is thus stated to be in the range 5.87–35.47 billion ISK. To place these figures into a broader economic perspective, economic growth in Iceland between 2010 and 2011 was approximately equal to 152 billion ISK (Statistics Iceland, 2017); thus, the marginal change in the total economic value of Heiðmörk is approximate to between 3.86% and 23.34% of the annual increase in national economic output occurring at the time of the survey.

As this paper does not contend that there is a single correct welfare estimate to choose from the three aggregate economic values, a further contemplation emerges in terms of what would be the correct aggregation to enter into an actual cost-benefit assessment. In a cost-benefit assessment one aggregate value will be chosen, and there are many benefits to using the total WTP value for the one-year tax over the alternatives, despite this choice being perhaps the least credible in terms of its assimilation with the usual duration of additional lump-sum taxes. First, the potential impacts of the temporal embedding of payments and likelihood biases are vanquished. Second, the choice of a one-year lump sum tax avoids the problem of having to choose an appropriate discount rate to apply to payments made in the future, a limitation that is exacerbated if some or all participants happen to have already discounted the future when providing their WTP estimate. Third, participants only have to undertake a WTP estimate based on their current budget constraint, as opposed to undertaking a potentially difficult conjecture about their future disposable income. Fourth, although environmental public goods such as Heiðmörk typically change little in character from year to year, long-term payments to secure the area's preservation introduce the risk that the characteristics of the resource being paid for in the future will not be the same as now, violating the basis of the survey's scenario.

4.2. Economic valuation and decision-making

Ruhl (2007, p. 761) states, *"failure to refine our understanding of their economic values, and the consequent inability to account for those values in regulatory and market settings and, more importantly, in the public mind, is unlikely to promote the preservation of natural systems."* The highlighting of the marginal change in Heiðmörk's total economic value through this contingent valuation study will inform the debate concerning potential trade-offs in its future land uses. However, although non-market valuation techniques are essential in order to account monetarily for the non-market total value of the environment and progress more informed decision-making, the range of values obtained in this study may be insufficient to fully represent the true value of Heiðmörk's many ecosystem services. For example, it has been reported that the marginal economic value of additional units of a specific ecosystem service varies greatly, and in the case of biodiversity is frequently very low (Simpson et al., 1996). Often this is due to limited scientific understanding of biodiversity impacts on the part of researchers and contingent valuation survey participants (Splash and Hanley, 1995; Pearce, 2001). Due to the limited capacity of money to express the value of certain ecosystem services, many practitioners argue along the lines that contingent valuation studies are only a critical primary step in advancing the information supplied to complete cost-benefit assessments, sufficient to stimulate a better informed debate about the merits of preservation versus development, but insufficient to lead to the absolute value representation of resources such as Heiðmörk in decision-making (Pearce and Moran, 1994; Splash and Hanley, 1995; Nunes and van den Bergh, 2001; Pearce, 2001).

4.3. Wider relevance of the CVM within decision-making for Icelandic development projects

In a global context, the use of economic valuation techniques as a basis for national and international policy-making has only developed over the last fifty years. Within the European Union, for example, the Treaty of Rome establishing the European Economic Community made no reference to the environment. However, from 1973, the Community progressively introduced environmental legislation via Environmental Action Plans (Pearce and Seccombe-Hett, 2000). The fifth Environmental Action Plan, *Toward Sustainability*, made specific reference to economic valuation techniques, stressing that these were necessary to a) take environmental impacts into account, and b) develop meaningful cost-benefit methodologies in respect of actions impinging on the natural resource stock (European Commission, 1992). In more recent times, similar policy rhetoric has been expressed within the OECD's

Environmental Performance Reviews of Iceland, all three of which have advocated that the nation should be strengthening its use of economic analysis in decision-making (OECD, 1993; OECD, 2001; OECD, 2014). In particular, the OECD's 2014 assessment emphasised that it was important for Iceland to *"develop some cost-benefit analysis process which gives appropriate consideration to all dimensions of power development (environment, tourism, social and regional development, project profitability)"* (OECD, 2014, p.115). Through the application of the CVM in this study, an approach is outlined that moves Iceland towards the eventual goal of fulfilling the OECD's recommendation.

5. Conclusion

The economic value of unspoiled natural areas and their many ecosystem services remains largely unaccounted for in Icelandic decision-making. In Iceland, cost-benefit assessments for development projects have omitted to incorporate the marginal costs of sacrificing the many benefits from environmental resources, despite the OECD repeatedly advising the nation of the need to conduct total valuation accounting. This paper presents the case study of Heiðmörk, the first application of the CVM to an Icelandic urban open space, one possessing a broad range of ecosystem services, together with complex management, ownership, and stakeholder arrangements. Although not a wilderness area as such, Heiðmörk demonstrates many of the fragmented characteristics of wild regions, with processes and species influenced by human interventions in terms of forestry management, grazing, recreational facilities, reservoirs, and road infrastructure. This study has estimated that the economic value of the environmental costs of developing Heiðmörk are in the range 5.87–35.47 billion ISK. The pathway of preservation for Heiðmörk should not be chosen on the basis of these outcomes alone, however, the results furnish decision-makers with an economic approximation of the resources' value to contemplate alongside the various forgone economic benefits associated with preservation. By definition, choosing the pathway of preservation for Heiðmörk ensures that the area retains its recreational value into the future, but necessitates that landowners forgo many alternative uses and associated economic benefits, including the value of the land owned by the municipalities of Reykjavík and Garðabær, forgone profits for would-be developers, and tax revenues for planning and governance agencies.

Additionally, this paper explored WTP patterns in response to three tax payment durations of either one, five or ten years. Three sizeable and representative sub-samples were formed from an initial group of 1608 individuals in favour of preservation. Although longer tax payment durations may be more credible in terms of their similarity to typical government practice, the results suggest that they may encourage certain biases, including potentially a temporal embedding of payments and likelihood bias that the good will be provided. Instead, as there are many complexities with regards to the validity and interpretation of WTP estimates relating to multiple payments into the future, the most appropriate welfare estimate to enter into cost-benefit assessments remains the value aggregated from the mean one-time payment, even if this value may be prone to being a low-estimate of the true total economic value of an environmental good.

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7. Summary and discussion

7.1 Summary

This body of research focuses on two empirical tiers of analysis particular to Iceland: firstly, the national level, through the development of a methodology for measuring environmental sustainability, and, secondly, the project-specific level, through estimations of the total economic value of environmental impacts associated with the development of high-temperature geothermal fields. There are considerable areas of conceptual overlap between the themes, which are of direct relevance to decision and policy-making. Understanding the full economic gains or losses associated with developing geothermal fields is a necessary pre-condition in order for decision-makers to determine whether it is optimal to develop or preserve such landscapes. In the absence of such information, decision-makers may approve projects which lead to the multiple and simultaneous sacrifice of ecosystem services, undermining environmental, economic and social components of sustainability.

Paper I combines a top-down and bottom-up approach to the delivery of a new methodology for the selection of indicators of environmental sustainability, specific to the national context. Using a mixture of expert judgment and the insights gained from focus group research, indicators were selected from a pool of options. Many existing indices of environmental sustainability have sought to compare performance between countries, leading to a certain remoteness in terms of context, but the methodology developed in Paper I was focused entirely on the specificities of the national context. The research draws upon the case studies of Iceland and Norway to illustrate how differentiated targets could be embedded into the analytical framework, thus potentially stimulating progress towards more environmentally sustainable outcomes. Analytical tools – radar charts and traffic-lights – provided a non-technical means of communicating performance outcomes, with the aim of providing easy-to-understand outcomes for policy-makers.

Paper II describes how Iceland's decision-making framework for energy projects is currently weakened by a regulatory gap connected to the economic valuation of environmental impacts, one that could potentially lead to the approval of projects which undermine social welfare. In addition, the paper described how understanding of the ecosystem services associated with geothermal areas – in Iceland, but also around the world – is to date very limited. Paper II highlights the example of the approach commonly adopted in the US connected to environmental regulations, whereby cost-benefit analyses include non-market valuation techniques to account for the economic value of environmental impacts. The paper concludes that a similar approach could easily be adopted in Iceland, but would require further legislation. The new approach, which would require developers to conduct independent cost-benefit analyses, could be based on the EPA's 'Guidelines for Preparing Economic Analysis'. The National Planning Agency, Skipulagsstofnun, would have responsibility for ensuring compliance with the guidelines, whilst the National Energy Authority would be allocated the power to reject projects failing the cost-benefit test.

Paper III advances understanding, in a general and thematic sense, of the ecosystem services most likely to be impacted through the development of a geothermal power project. This article also contemplated whether non-monetary or monetary information is best suited to estimating the change in provisioning of each service, and also reviewed the sources of information that could be used to establish the qualitative change. Paper III concluded that the scope of cost-benefit assessments should be limited to value impacts to ecosystem services which are decidedly utilitarian in nature, including those connected to the sacrifice of provisioned resources, recreational amenity, and cultural associations linked to non-use notions of economic value. In decision-making, monetary information was found to be an inappropriate metric for the more philosophical ecosystem services associated with geothermal areas, such as spiritual enrichment or artistic inspiration. Thus, Paper III concluded that a pluralist approach involving the use of monetary and non-monetary sources of information is best for valuing ecosystem service impacts in a geothermal context. In addition, Paper III considered Environmental Impact Assessments closest to fulfilling the information requirements of environmental economists in a geothermal context, although often there is a need for greater stakeholder consultation in order to better understand the character and extent of impacts to human well-being.

Paper IV communicates the results from the contingent valuation studies of Eldvörp and Hverahlíð, which are the first estimates of the economic value of preserving geothermal fields since the only prior study by Thayer (1981). The estimated mean WTP for preservation of these areas is 8,333 ISK and 7,122 ISK for Eldvörp and Hverahlíð respectively. When scaled up to the Icelandic population of taxpayers, these results were both found to equate to approximately 2% of the estimated total construction costs of US$ 800,000,000 for Iceland's largest geothermal plant at Hellisheiði. Their scale is potentially significant, perhaps to the extent that a developer may opt not to proceed with a particular project. Furthermore, the scale of these outcomes provides evidence in support of the OECD's call for Iceland to set up cost-benefit procedures which account for the economic value of the environmental impacts of power projects.

Paper V reports the results from the contingent valuation study of Heiðmörk, an urban park with diverse landscape features and recreational amenities on the outskirts of Reykjavík. The estimated mean WTP for preservation of Heiðmörk was in the range of 17,039 to 24,790 ISK per payment. In addition, it is also found that the increased duration of a fixed payment vehicle – in this case, an additional lump-sum tax – is associated with much higher total economic valuations than compared to a one-year payment period.

Paper I provided a methodology for measuring environmental sustainability in a national context. Many of the environmental impacts captured within the selected indicator set are derived from energy – in terms of generation and how it is used. Ensuring that the environmental impacts of power projects are given full arbitrage in decision-making was central to the OECD's call for improved accounting practices in Iceland. Paper II set out arguments in support of Iceland heeding the OECD's call and the steps necessary to incorporate such accounting measures for all of Iceland's future energy projects. Paper III focused in more depth on the environmental and ecosystem service impacts particular to the harnessing of high-temperature geothermal fields. In Paper III, consideration was given to the scope of monetary information with respect to the ecosystem service impacts likely to be associated with developing geothermal areas. In so doing, the limits of cost-benefit analysis were determined with regards to the assessment of the economic value of environmental impacts connected to geothermal power projects. The results from the studies in Papers IV and V provide (a) an indication of the likely scale of the economic value associated with geothermal power projects in high-temperature fields, and (b) suggest the need for further economic valuation studies related to all landscape types in Iceland. Much greater understanding is required in Iceland of the type and scale – temporal and spatial – of ecosystem services associated with Iceland's diverse landscapes. Through the cultivation of understanding concerning the scale and economic value of the nation's ecosystem services, both from the perspective of the producer and consumer, there is greater likelihood of decision-makers choosing to preserve rather than develop valuable landscapes, avoiding irreversible environmental change. Therefore, such knowledge can be indirectly beneficial in terms of promoting environmental sustainability across all spatial scales, up to and including the national level explored in Paper I.

The structure of this concluding chapter is as follows. Section 7.2 begins by discussing in more detail some of the main outcomes and implications from the research. Section 7.3 outlines the contribution of this thesis in terms of advancing practical and academic knowledge. Section 7.4 provides recommendations for decision and policy-makers based on the outcomes of this thesis. Section 7.5 evaluates the limitations of this thesis connected to its research methods. Section 7.6 considers options for further research. Section 7.7 provides a concluding statement.

7.2 Discussion of results

In this section, the results from the five papers will be discussed in terms of:

- Measuring environmental sustainability in a national context
- Valuing ecosystem service impacts connected to the development of geothermal areas
- Knowledge about ecosystem services in Iceland
- Decision-making involving the use of environmental sustainability indicators and non-market valuation techniques.

7.2.1 Measuring environmental sustainability using a national spatial scale

Measuring environmental sustainability in a national context requires a comprehensive set of indicators, revealing performance across it multiple dimensions (Jordan and Lenschow, 2009; Fiorino, 2011; Moldan et al., 2012; Dobbie and Dail, 2013). In Paper I, the approach to selecting indicators of environmental sustainability grew out of a clear depiction of the concept, commencing with Goodland’s widely cited definition. Describing environmental sustainability as involving the protection of raw materials and ensuring that sinks for assimilating waste substances are not exceeded (Goodland, 1995), Goodland set out the need for reconciliation between the flourishing capacities of ecosystems and promotion of human welfare through economic activities. Thus, if natural resources are depleted to levels whereby they are unable to restore themselves or provision the same quantity and quality of ecosystem services, economic activities that rely on them are unsustainable.

In recent years, the focus of composite indices of environmental sustainability, such as the Environmental Performance Index, has been on comparing national performance according to perceived global commonalities: generic policy targets and selected indicators (Heink and Kowarik, 2010; Moldan et al., 2012; Olafsson et al., 2014). Whilst this approach is valid to some extent, the research of Olafsson et al. (2014) has demonstrated the flaws of international harmonisation in measuring national environmental sustainability performance. As an international comparison of performance was not an objective of this research, there was thus no attempt to aggregate indicators, apply weightings and arrive at a composite value.

The focus of the methodology delineated in Paper I has not been to reject international harmonisation out of hand, but rather to recognise the limitations of genericism and cultivate an approach more likely to retain the political relevance of indicator outcomes. Thus, targets were differentiated for certain indicators in the two case study examples of Iceland and Norway. The paper set out a clear rationale for the selection or rejection of indicators based on participatory processes, which helped to enable the multiple dimensions of environmental sustainability to be captured. Efforts were made by the expert team to ensure that the selected indicators, whilst broad in scope, were limited in number, as well as being clearly documented and explained in terms of what they were measuring. In terms of data, priority was given to the use of official statistics as far as possible, such as those deriving from the UNFCCC and EUROSTAT databases. This was done to try and ensure the timeliness and quality of data, with the ambition that all data would be available on an annual basis with minimal lags. In reality, there remain data gaps limiting the comprehensiveness of the selected set of indicators, as Section 7.3 acknowledges.

Maintaining the political relevance of the selected set of indicators was deemed to be essential. Otherwise, indicators provide mere snapshots of performance and are of little relevance to policy design, follow-up and assessment. In Paper I, performance targets for indicators, wherever these could be applied, were adopted following an extensive review by the expert team of pertinent national and international standards. In some cases, the benchmarks for the case studies of Iceland and Norway were identical, such as in the case of common European objectives for the recycling of waste; in other cases, such as for targets related to greenhouse gas emissions, these were differentiated. The differentiation of targets is considerate of the political realities of improving a nation's environmental performance, even when the specific environmental issue of concern is global in character. Where targets could not be applied to certain indicators, trend-based evaluations over time were applied, in order to try and promote continual progress. Time and effort was spent considering the optimal means of communicating indicator outcomes. Through graphical representation in the form of radar charts and traffic-lights, the interpretability of the indicator set was enhanced.

7.2.2 Valuing ecosystem service impacts connected to the development of geothermal areas

Much attention in the academic literature has been allocated to the environmental benefits of utilising geothermal energy compared to fossil-fuel alternatives (Brophy, 1997; Fridleifsson, 2001; Glassley, 2014). Until Paper III, although considerable academic attention has been given to the environmental impacts of developing high-temperature geothermal fields (Axtmann, 1975; Ármansson and Kristmannsdóttir, 1992; Kristmannsdóttir and Ármansson, 2003; DiPippo, 2012), very little focus has been afforded to the related ecosystem services context. To date, the only previous academic study to consider the potential ecosystem service impacts in a geothermal context was the paper by Hastik et al. (2015), which was limited to a brief consideration of impacts to regulating services. Although the CICES classification was used, no impacts were listed connected to provisioning or cultural ecosystem service impacts. Paper III's thematic review is comprehensive, establishing that ecosystem services belonging to all three main typologies – again, as per the CICES classification – have the potential to be impacted through the development of a geothermal power plant. From provisioning services, such as rare genetic materials, to regulating services, such as water purification, to cultural services, such as recreational amenity, a multitude of ecosystem services may be sacrificed simultaneously via the development of geothermal power.

Although Paper IV applied the contingent valuation method to estimate the total economic value of environmental impacts pertaining to the development of geothermal power, there remains only piecemeal knowledge concerning the economic value of changes to the provisioning of specific services. The results obtained in this thesis, whilst confirming that geothermal landscapes in Iceland have considerable total economic value, spawn many questions about the details. What, for instance, is the projected change in the economic value of recreational amenity in response to the development proposals at Hverahlíð and Eldvörp? What might be the economic value of damages to human health from increased hydrogen sulphide emissions by testing new boreholes at Eldvörp? Economic valuation methods could also be used to value marginal changes in regulating ecosystem services, for example, through the replacement costs method or the social costs of carbon from Integrated Assessment Models such as FUND.

Paper III articulated the non-market valuation techniques that could, in theory, be applied to estimate the economic value of impacts to specific ecosystem services. In practice, in a geothermal context, their adoption will be challenging. This thesis has, for instance, avoided investigating the economic value of changes in provisioning resources at Eldvörp and Hverahlíð due to reasons of limited time and resources, and a desire for the outcomes of the research to be of relevance to decision-makers. Establishing the scientific links between the input of resources, such as silica, and eventual quantity and quality of product outputs, such as nourishing skin creams, is in itself complicated. Estimating the economic value of changes in the provisioning of such materials from a single geothermal resource is, again, very difficult through the production function method, especially since multiple substitute sites exist in Iceland. However, some opportunities are available, in a practical context, to explore the economic value of impacts to specific ecosystem services, and Section 7.6 pontificates on these.

It could be hypothesised that the economic value of changes to provisioning and regulating ecosystem services in Iceland is very small connected to the development of geothermal areas, albeit this is an untested hypothesis. The feedback provided by survey participants in the contingent valuation studies of Eldvörp and Hverahlíð added a weight of anecdotal evidence, suggesting that preferences for the preservation of geothermal areas in Iceland were predominantly linked to recreational amenity and value associations connected to the rarity, pristineness and diversity of such landscapes. Geothermal fields such as Eldvörp are characterised by rare and colourful landscapes, hot springs and lava fields, and development proposals can impact on these across a large area. At Eldvörp, if HS Orka's proposals exploratory drilling proposals are realised, each of the future test boreholes will provide only a few MW of power, but will be located across a large area and disturb lava fields formed within the past 1,000 years. In the case of Hverahlíð, if a geothermal power plant was to be constructed as per Reykjavik Energy's proposals, the landscape will be disturbed aurally and visually through the erection of plant infrastructure, roads, pipes and power lines.

As Paper III describes, sometimes geothermal landscapes are associated with human values that go far beyond utilitarian notions. Ecosystem services such as artistic inspiration and spiritual enrichment derived from geothermal areas are often strongly felt and have decidedly intrinsic underpinnings. Far from being purely subjective values of relevance to the individual, these ecosystem services are often tied in with well-being benefits for mankind and the world as a whole. Seeking to value preferences for these ecosystem services in a utilitarian manner through non-market valuation is typically inappropriate; indeed, the elicitation of economic data connected to these values may even contribute to the undermining of such fragile resources. Rather, voice to those benefiting from such ecosystem services should be given through non-monetary approaches, including deliberative methods. A sympathetic government is also necessary to ensure the inclusion of such values and their full arbitrage in decision-making processes.

7.2.3 Knowledge about ecosystem services in Iceland

In a global sense, ecosystems and their associated services are increasingly under threat. In 2005, the Millennium Ecosystem Assessment concluded that 15 of the 24 assessed ecosystem services were already in decline or being degraded (MEA, 2005). Recent national assessments in the United Kingdom and Spain concluded that 45% and 30% of their respective ecosystem services have deteriorated at the national scale (UKNEA, 2011; Santos-Martín et al., 2013).

Iceland is a nation possessing a very broad range of landscapes, including desert highlands, geothermal areas and related features, glaciers and related features, lakes and rivers, agricultural fields, coastal regions and urbanised areas. Given the harshness of the climate and fragility of the most common landscape types, which are fundamental to the nation's identity and burgeoning tourism economy, it is surprising that so little research has been conducted connected to derived well-being benefits. Besides the outcomes in Paper's IV and V and those currently emerging from other components of the Heiðmörk valuation project, there is very little knowledge concerning the type, scale, quality, quantity and economic value of the nation's ecosystem services. Paper II included a brief summary of the small handful of non-market valuation studies conducted in Iceland connected to ecosystem services.

In the absence of baseline studies, it is impossible to gauge the contribution that Iceland's ecosystem services make to human well-being, and nor whether such provision has deteriorated over time. Concerns about the environmental sustainability of tourism activities have been expressed in Iceland (Van Houtte, 2015; Granquist and Nilsson, 2016; Sæþórsdóttir and Saarinen, 2016). Although these studies and their surveys are important contributions in their own right, they are disconnected from the type of evaluation of changes in well-being benefits that could be delivered through an ecosystem services perspective to landscape change.

7.2.4 Decision-making involving the use of environmental sustainability indicators and non-market valuation techniques

Embedding new methodologies into decision-making is often a challenging task in any environmental context. There are precedents in terms of the use of environmental sustainability indicators on a national scale. The cases of Ireland and Canada were cited in Paper I as examples of nations that have incorporated environmental sustainability indicators as performance monitoring devices (EPAI, 2012; ECCC, 2013). However, the use of such indicators remains far from widespread, which risks entailing a situation whereby decision-makers have a poor understanding of environmental performance and trends at the macro scale. This is despite the clear benefits to governance institutions in terms of better understanding the environment-economy nexus from an aggregate perspective and facilitating greater accountability.

It is not within the remit of Paper I – a methodological study – to delve deeply, however, the logical progression of the methodology is its application to full analysis of underlying economic factors. One of the key roles of environmental sustainability indicators is as an early-warning tool, identifying risks and problems (WRI, 1995). In so doing, decision-makers can design and refine strategies, potentially commencing new policy initiatives to correct unsustainable outcomes. This task is made easier when the methodology embeds pre-existing performance targets, specific to the national context, into its reporting mechanisms.

It is the collective gathering of data and annual reporting of performance against targets over time that differentiates Paper I's methodology from a loose set of data, which would be incomprehensible to a decision-maker seeking to establish the acceptability of outcomes. This is an essential difference between the approach taken in this thesis and the OECD's periodic Environmental Performance Reviews of member states (OECD, 2001; OECD, 2011; OECD, 2014). Both approaches facilitate the reporting of environmental information and trends over time, enabling an informed commentary to be developed comparing performance against nation-specific targets. However, a failure to utilise indicators and calibrate performance directly against targets reduces the decision-making relevance of the OECD's approach – the early-warning and accountability advantages of indicators are lost. The approach advanced in Paper I is based on a common methodological framework to selecting indicators, one which has sought to strike a delicate balance between the input of experts and the public, scientific validity, technical feasibility and political acceptability. Furthermore, the graphical reporting techniques promoted in Paper I help to advance the methodology in terms of ease of understanding for decision-makers, policy-makers and the public.

Over the past three decades, the pursuit of environmental sustainability – based upon a precautionary approach to science – has gained broad acceptance amongst political stakeholders the world over. The implementation and embedding of environmental sustainability in decision-making requires information in clear frameworks – as per Paper I – but also often necessitates cognitive shifts on the part of decision-makers. Often decision-making is viewed as a rational process, whereby the provision of greater and better information leads to more environmentally sustainable outcomes (Bell and Morse, 2008). However, in reality, decision-making is often undertaken via a 'fuzzy process' based on a number of subjective factors related to ideology, values, norms, interests, power relationships and institutional contexts (Waas et al., 2014). Therefore, the provision of improved and structured information about the environment, whilst intellectually appealing in terms of stimulating evidence-based decision-making, may be insufficient to affect outcomes. Without the transformation of the environmental sustainability concept from an action-guiding to action-generating and forward-looking principle at the fulcrum of decision-making, there may continue to be limits and resistance to the adoption of environmental sustainability indicators on a national scale.

Although often applied in the context of environmental regulations in the US (Ruhl, 2007), there is no evidence of the widespread use of ecosystem service valuations in decision-making. This is despite many publications calling for the measurement of monetary values to reflect the social importance of ecosystem services and stimulate better management decisions (Randall, 1988; Daily et al., 2009; Costanza et al., 2014). The comprehensive literature review by Laurans et al. (2013) found that the use of ecosystem services valuations is overwhelmingly limited to academic studies, which tend to include suggestions for further use in decision-making. Thus, such studies are predominantly focused on information gathering and awareness-raising. As Paper II discusses in the context of Icelandic energy projects, the potential for decision-makers to make sub-optimal decisions from an economic welfare perspective can be reduced by (a) embedding cost-benefit analysis as a mandatory requirement in license applications, and (b) requiring cost-benefit analysis to be conducted by an independent practitioner according to prescribed guidelines. In so doing, there is the potential to overcome the type of subjective, vested and 'fuzzy process' associated with decision-making and discussed in the context of environmental sustainability indicators.

Paper II discussed how Iceland's overarching legal and regulatory system connected to energy projects incorporates environmental sustainability principles, such as in the Nature Conservation Act. At the top tier of the body of legislation, The Master Plan for Nature Protection and Energy

Utilisation is undoubtedly an expression of a precautionary approach to development. However, its influence is strategic, stipulating the suitable location of energy projects, not establishing the acceptability of specific proposals. The use of non-market valuation techniques within cost-benefit analysis, as a component in the decision-making process, is compatible with the precautionary principle and environmental sustainability objectives.

As has been discussed, in Iceland knowledge is very limited concerning the economic value of impacts to ecosystem services provisioned from geothermal areas. Given this uncertainty and the irreversibility of some environmental impacts caused by geothermal power projects, such as the construction of new roads on lava fields, it is all the more important that preferences are elucidated, quantified and included in welfare analyses. As well as potentially preventing new energy projects in certain cases, the gradual expansion in knowledge about the economic value of environmental impacts from geothermal areas could demonstrate the merits of governments taking action to address market failures resulting from excessive damage. Through this process, extended cost-benefit analysis can play an important role in promoting more environmentally sustainable developments.

7.3 Contribution to academic and practical knowledge

7.3.1 Academic

This thesis has made a number of contributions to academic knowledge. A number of scholars have set out general guidance on how best to measure environmental sustainability, including in a national context (Jordan and Lenschow, 2009; Fiorino, 2011; Moldan et al., 2012; Dobbie and Dail, 2013). Paper I goes further than existing studies by delineating a five-stage methodology for selecting indicators of environmental sustainability and how to report outcomes. The use of case study illustrations promotes the replicability of the approach.

Paper II has an academic value by adding to the existing literature concerning the potential for projects to be approved which result in a net loss in social welfare, given the absence of non-market valuation techniques in cost-benefit analysis (Pearce, 1998; Dixon et al., 2013; Harris and Roach, 2013). Its main contribution, however, is contextual. Paper II is the first academic study to review a nation’s existing body of energy policies and legislation, and then to argue the case for the integration of non-market valuation techniques into the decision-making apparatus. Moreover, Paper III outlines the legislative and procedural steps necessary to incorporate such accounting measures, which may have a wider applicability to other policy contexts connected to natural resources.

In the context of ecosystem services connected to geothermal areas, this thesis has begun to fill a notable gap in the academic literature. Apart from a very brief review by Hastik et al. (2015), which focused on only one type of service, there have been no prior studies looking at the ecosystem services likely to be impacted by the development of a geothermal power project. The study by Hastik et al. was also limited to ecosystem service impacts and classification, not proceeding to the next stage of considering how the respective affects should be valued and the applicable methods. Paper III thus contributes to the academic literature by providing the first comprehensive thematic review of ecosystem service impacts connected to geothermal power projects, with specific regards to their type, how they should be valued, and what sources of information are best for environmental economists to use in order to communicate changes in their provisioning.

In terms of understanding the economic welfare implications of developing geothermal power projects, only one previous estimate is reported in the academic literature, the contingent valuation study by Thayer (1981). Thus, Paper IV considerably advances and updates academic knowledge through the provision of two cost estimates of the economic value of environmental impacts associated with developing a geothermal power project.

The academic literature contains a number of studies concerning the preservation value of urban parks (McConnell and Walls, 2005; Brander and Koetse, 2011; Dekkers and Koomen, 2012). There have been no such valuation studies in Iceland, and thus the draft of Paper V adds to the existing literature and provides a new context. As far as the author is aware, there are no economic valuation studies concerning the preservation of urban parks which have been heavily influenced by geothermal activities, leading to the formation of lava fields, pseudo-craters and lakes. Furthermore, Paper V researchers a lightly explored area of the contingent valuation literature: sensitivity of scope to payment vehicle duration. A small number of studies, based on low sample sizes, have reported that the total economic value of public goods can be considerably larger when the commitment involves multiple rather than one-off payments (Rowe, Schulze and Hurd, 1986; Carson et al., 1992; Kahneman and Knetsch, 1992). Paper V reports similar findings based on much larger sample sizes, potentially supporting Kahneman and Knetsch’s (1992) contention of a temporal embedding of payments.

7.3.2 Practical

Regardless of whether indicators are used instrumentally, the process of indicator selection involved in Paper I facilitated the intangible concept of group learning and ideas sharing during the focus group stage of research. With regards to decision and policy-makers, the use of the methodology and further analysis of outcomes would help to better understand the effects of economic activities on environmental sustainability in a macro context. It only by understanding performance against future targets and current trends that corrective policies can be set in motion. The method of selecting indicators of environmental sustainability could also be applied to other countries, beyond the two case studies of Iceland and Norway. After all, one of the main aims of this study was to formulate a method particular to the national context, not replicate existing standards that seek to directly compare outcomes across multiple countries.

Paper II responds to the OECDs call for Iceland to set up accounting measures which incorporate an economic valuation of the environmental impacts of power projects. Its contribution is, therefore, decidedly practical. Paper II sets out how economic assessments of environmental impacts could be incorporated into the decision-making framework with regards to license approvals, an approach that is likely to be of keen interest to officials within Iceland's government, the National Energy Authority and National Planning Agency, and resource owners.

The practical value of Paper III centres around the linking of likely ecosystem service impacts deriving from geothermal power projects to the total economic value framework and most suitable non-market and non-monetary valuation techniques. The general thematic review should act as a useful reference guide for practitioners in the future. Furthermore, Paper III determined that Environmental Impact Assessments currently represent the most suitable source of information for environmental economists seeking to conceive of realistic scenarios of qualitative change in contingent valuation surveys. This understanding gleaned practical benefits during the process of designing the contingent valuation surveys in Paper IV.

The methods and results set out in Paper IV have considerable practical value. Firstly, they help to set out a methodology that could be applied to fulfil the OECD's demand for Iceland's cost-benefit analyses particular to energy projects to account for environmental impacts. Secondly, the study outcomes are useful for owners and managers of energy resources in Iceland. With the likelihood that such accounting procedures will become mandatory in the future, the studies help to build knowledge and expertise in Iceland, which will be useful to energy companies, engineering firms and public officials. Due to the novelty of applying non-market valuation techniques to the field of geothermal energy, as well as developing and testing them in an Icelandic context, the Icelandic research arena within this field has been greatly enhanced and can contribute to the nation leading the way internationally in sustainable geothermal utilisation and assessment.

The results in Paper V provide useful information for the multiple resource owners and the Icelandic public, many of whom frequent Heiðmörk on a regular basis. In the future, should the municipalities of Reykjavík and Garðabær wish to develop Heiðmörk, the results in this study could form a useful informative for decision-makers and lobbyists, who may wish to consider the estimated total economic value of its many ecosystem services. The economic gains and tax revenues deriving from any development project could be compared against the economic benefits of preservation.

7.4 Recommendations

The outcomes of this thesis lead to the formulation of four main recommendations for policy and decision-makers. These are as follows:

- To commence analysis of Iceland's environmental sustainability performance using the proposed indicator set, as part of an overall strategy for gaining understanding about linkages between national economic activities and environmental impacts. The use of a 'distance-to-target' and trend-based approach to reporting indicator outcomes should encourage policy-makers to instigate new research and policy initiatives, if corrective action is required.
- To further debate the merits of incorporating independently prepared cost-benefit analyses (including non-market valuation techniques) as a mandatory component of the decision-making basis with regards to energy projects. This will help to progress the nation towards the fulfilment of the OECD's request for Iceland to utilise such accounting practices.
- To instigate further research into the economic value of ecosystem services impacted by all energy projects in Iceland, including geothermal, hydro power and wind energy.
- To consider incorporating non-market valuation techniques as a component of the evaluative process within the Master Plan for Nature Protection and Energy Utilisation.

The methods adopted in this thesis would help to increase stakeholder involvement in decision-making. The insights gained from focus groups helped to guide to the indicator selection process, whilst the methodology in the contingent valuation studies was inherently participatory through its focus on a representative sample of the Icelandic population. In terms of the environmental impacts pertaining to Icelandic energy projects, there could become two core stages of participation on the part of the public: (1) qualitatively, during the formation of the Environmental Impact Assessment, as is already widely recommended, and (2) monetarily, in response to the impacts of final design proposals through the use of stated preference techniques.

7.5 Limitiations

In this section, the limitations and weaknesses of the study are discussed with respect to the research methods used: environmental sustainability indicators as a measure of environmental sustainability and non-market valuation techniques. The latter focuses on the contingent valuation method due to its use in Papers IV and V, however, other non-market valuation techniques are associated with potential weaknesses. These issues have been discussed in Table 1 of Paper II.

7.5.1 Environmental sustainability indicators as a measure of environmental sustainability

The methodology for selecting environmental sustainability indicators stressed the lack of comprehensiveness found in existing indices, based upon a case study review of Iceland (Olafsson et al., 2014). As with any indicator selection process seeking to integrate the insights of expert judgment and focus groups, there remains the capacity for subjectivity to cloud the debate. Reconciling focus group insights and weighing the various opinions against expert judgment was an informal but complex process, which, if repeated, may lead to slightly different indicator choices.

In developing a new methodology for the selection of environmental sustainability indicators, bespoke to a national context, it has to be acknowledged that comprehensiveness was not delivered, but remains a realistic aspiration provided the described data gaps are filled. The explicit acknowledgement of data gaps in the national context represents the first stage in examining future data requirements and new potential indicators. There are a number of prominent examples in the cases of Iceland and Norway connected to missing indicators, and these are reviewed in Paper I. The most obvious case, which relates to the sustainability of fisheries, is relevant to most countries. As discussed in Paper I, a suitable metric specific to the national context does not yet exist. Reliance on the approach taken by the Environmental Performance Index, which sources its data from the Sea Around Us Project (Pauly et al., 2013), leads to misleading conclusions in a national context. Indeed, any approach basing its conclusions on the sustainability of fish stocks on catch data is unsound, particularly in cases where the catch has reduced due to management techniques and not a decline in stock abundance.

A ubiquitous concern with regards to the usefulness of the methodology involves the issue of time lags. To move towards environmentally sustainable outcomes, policy-makers require timely information which demonstrates whether a system is becoming more or less sustainable, and specific information on the aspects requiring the most improvement (Mayer, 2008). Environmental indicators compete with economic information and, at the moment, the latter sets the standards for timeliness and frequency. Data on Gross Domestic Product and its constituent elements is typically published only a few months after the relevant accounting period; data used in environmental indicators is commonly published two years or more after the year in question. In some cases, data preparation is irregular, such as in the case of the National Reports on Biodiversity prepared to satisfy the Convention on Biological Diversity. There are frequently five-year gaps between assessments for certain nations, including Iceland. Where time lags exist or the publication of data is irregular, there is the inherent risk that information presented in environmental indicators is greatly reduced in political relevance. Estimates can be made based on prior data trends, but these entail obvious risks relating to their assumptions and approximations.

Embedding politically agreed targets into the reporting mechanisms of the methodology ensures the relevance of the selected indicator set, but targets set by national or international governance bodies do not necessarily reflect thresholds for environmental sustainability. They are often, at best, examples of political satisficing. For example, few would consider that establishing 17% of Iceland's terrestrial and inland water areas – as required by Aichi, Strategic Goal C, by 2020 – equates to an ideal state of environmental sustainability. However, an alternative approach, that fails to incorporate target measures set by international standards or targets unachievable goals, risks reducing any set of environmental sustainability indicators to irrelevance. As Moldan et al. (2012, p.7) assert, *"The existence of a target is of key importance, regardless of the type of target. Even a vague, qualitative target may be an important policy driver stimulating both research and policy debate on the desirable state of the issue to be achieved. The benefit of specific, quantitative, time bound targets is then straight-forward: the indicators can be link to them and interpreted clearly on a distance-to-target basis."* Without targets, the accountability aspect of performance cannot be fairly determined. Moreover, the integration of targets into the methodology, specific rather than generic to the national context, aims to drive continual environmental progress, and the same is true of indicators without targets, but are evaluated on a trend basis. Furthermore, Paper I acknowledges that as new targets emerge for future time periods, these should replace older standards, which have hopefully been met.

Critics of the proposed methodology may contend that by focusing on political expedience, it fails to meet its stated objectives of measuring environmental sustainability. There can be no satisfactory reconciliation to this debate, however it is important to stress that the use of analytical tools for measuring environmental sustainability should be confined to an indicator set. A wide-variety of additional approaches may be necessary to supplement the contribution made by a bespoke indicator set (Esty and Porter, 2005; Wilson et al., 2007; Olafsson et al., 2014).

One such option could be the Ecological Footprint, which calculates the amount of biologically productive land and marine resources necessary to support a national population at its current level of consumption (Wackernagel and Rees, 1997). Although not directly relevant to decision-making, the Ecological Footprint is able to highlight sources of ecological deficit, which may indirectly help to promote the formation of corrective policies connected to land-use management.

Another metric, which takes one further step than the Ecological Footprint, is the Genuine Progress Indicator (Cobb et al., 1995). Focused primarily on the issue of the sustainability of economic activity rather than environmental sustainability, it nevertheless adjusts Gross Domestic Product for many of the environmental and social costs associated with national economic activity. In so doing, countries can gain an impression of the long-term sustainability of their economy and an approximation of the economic value of various environmental costs, such as air and water pollution, greenhouse gas emissions, and losses of wetlands.

Ultimately, irrespective of the indices that are used in analysis by policy and decision-makers, progress towards environmental sustainability requires the formation of a political consensus on a national and international scale about the importance of the concept. Despite the presence of seminal publications such as the Millennium Ecosystem Assessment (2005), the world is less environmentally sustainable than it was a decade ago and continuing on this pathway. The results in environmental sustainability indicators can illuminate the issues and challenges, but only political willpower determines whether, how and how quickly societies will transition towards objectives.

7.5.2 Non-market valuation techniques – contingent valuation

In Papers IV and V, the contingent valuation method was selected as an appropriate means of forming an estimate of the total economic value of Eldvörp, Hverahlíð and Heiðmörk. Particularly in the cases of Eldvörp and Hverahlíð, this was due to the perception that non-use value would represent a significant proportion of total economic value, as well as for reasons of limited resources which prevented the use of multiple non-market valuation techniques for specific ecosystem services. Although not discussed in any level of detail in Papers IV and V, the use of stated preference techniques – and the contingent valuation method in particular – has been hotly debated over the years, with concerns and counter-claims regarding the validity of its approach. This section briefly discusses some of the background to the use of the contingent valuation method and the main contentions about its validity.

Although widely used in environmental regulatory analysis throughout the 1980s, debate concerning the validity of the contingent valuation method only really gained prominence following the Exxon Valdez oil spill in Alaska's Prince William Sound in 1989. The study estimated preferences and willingness to pay to avoid a similar incident, which amounted to total damages of $2.8 million and was based almost entirely on non-use values (Carson et al., 2003). The study outcomes were widely scrutinised, with the debate focused on whether people could express accurately their preferences for non-use environmental outcomes through the medium of a survey. In the aftermath of the debate, the US National Oceanic and Atmospheric Administration established a panel tasked with determining the efficacy of the method. The panel provided qualified support, stating that, *"contingent valuation studies can produce estimates reliable enough to be the starting point of a judicial process of damage assessment, including lost passive-use values"* (Arrow et al., 1993, p. 4610). The panel also set out a list of best practice design standards for contingent valuation surveys, measures which have been incorporated into the surveys used for Eldvörp, Hverahlíð and Heiðmörk, alongside a few modern innovations such as the use of a web-based format. These measures, such as the use of the double bounded dichotomous choice format, help to increase statistical efficiency and reduce bias compared to other approaches.

Despite the elements of standardisation advanced by the panel, the contingent valuation method remained subject to considerable criticism. Diamond and Hausman (1994, p.62) argued that *"contingent valuation is a deeply flawed methodology for measuring non-use value, one that does not estimate what its proponents claim to be estimating"*. Hausman (2012, p.54) added that *"despite all the positive-sounding talk about how great progress has been made in contingent valuation methods, recent studies by top experts continue to fail basic tests of plausibility"*.

Other academics have provided opposing evaluations. Carson (2012, p.40) argued that *"contingent valuation done appropriately can provide a reliable basis for gauging what the public is willing to pay to obtain well-defined public goods"*. Kling, Phaneuf and Zhao (2012) also provided evidence from experimental economics supporting the validity of stated preference methods.

One of the major contentions cited by academics is that there is a divergence between what people are willing to pay in a survey setting for an environmental good compared to if they were actually required to make the payment. Hypothetical and strategic forms of bias can never be totally eradicated, but can reduced through attention to how well the environmental good is defined and the incentive compatibility of the specified payment mechanism. Efforts were made in the contingent valuation surveys for Eldvörp, Hverahlíð and Heiðmörk to define the scenario of potential change carefully, providing full details of environmental impacts, and utilise the type of lump-sum additional tax that is common in Iceland. Although no experimental markets were applied after the respective contingent valuation surveys, studies have shown that incentive compatible and consequential payment vehicles can lead to similar elicitations of willingness to pay when compared with experimental evaluations (Laundry and List, 2007; Vossler and Evans, 2009). The use of experimental markets connected to future contingent valuation studies in Iceland would represent an interesting line of research and may provide supportive evidence to validate the survey findings.

A number of other contentions with contingent valuation surveys have been cited in the academic literature, all of which could have biased the welfare estimates in Papers IV and V. Researchers have found that stated preference estimates can be very sensitive to the way in which a survey is designed. Small variations in the design or layout of a survey can have a large influence on resultant elicitations of willingness to pay. These issues include:

- Estimates of willingness to pay tend to vary depending on the type of valuation questions asked, with single 'yes/no' questions (asking people whether they would or would not be prepared to pay a specific amount) providing higher estimates than other question types (Champ and Bishop, 2006; Carson and Groves, 2007). The use of 'yes/no' questions was the approach taken in the surveys for Eldvörp, Hverahlíð and Heiðmörk.
- Estimates of willingness to pay can be very sensitive to the specificity and detail of information provided about the environmental outcome and broader environmental context (MacMillan, Hanley and Lienhoop, 2006; Munro and Hanley, 1999). The results in the Eldvörp and Hverahlíð studies were thus dependent on the summary of environmental impacts abridged from the contents of Environmental Impact Assessments.
- The type of payment mechanism used can have a significant impact on willingness to pay, or can imply very high discount rates based on comparisons of one-off charges to annual payments (Kovacs and Larson, 2008; Rolfe and Brouwer, 2012). This latter affliction was evident in Paper V, whereby unconventionally high discount rates were necessary to equalise the three welfare estimates, which were based on payment durations of one to ten years.
- Survey participants often 'anchor' responses to numbers seen earlier in a survey, especially when asked several valuation questions, and may answer 'yes' to questions even when they are uncertain (Green et al., 1998; Day et al., 2012). Although the risk of anchoring was reduced in the three contingent valuation surveys through the use of the dichotomous double bounded choice bidding format, survey participants were still asked direct 'yes' or 'no' questions in terms of whether they had a willingness to pay and in response to bid offers. In addition, in these studies there was limited information available (small pilot studies) when setting the bid offers, and thus the design of future surveys should bear in mind the level of (yes, yes) responses and consider whether higher second bid offers are likely to be necessary.

In general, stated preference methods appear most likely to generate biased welfare estimates when survey participants have low familiarity with the non-market good being valued (which may be more likely when non-use value is being estimated), or when the good is described in a way that they do not find credible (Bateman et al., 2011). In the contingent valuation studies reported in Papers IV and V, the study sites were well-known to the majority of the national population and, particularly in the cases of Eldvörp and Hverahlíð, the study sites were associated with existing design proposals for further exploration and a potential power plant. Therefore, although sources of bias can never be entirely ameliorated, the credibility of these studies was enhanced via their considerable likelihood. There remains a risk of upward bias afflicting the results due to distributional assumptions, including the decision to not extend the distribution into negative WTP.

7.6 Further research

This thesis stimulates a number of possible future research lines connected to measuring environmental sustainability in a national context and the use of non-market valuation techniques specific to the ecosystem services provisioned by geothermal areas.

7.6.1 Measuring environmental sustainability

The methodology proposed in Paper I included a brief case study section relevant to Iceland and Norway. The case studies represented entirely descriptive and very brief accounts, since the main aim was to identify the differentiation of targets between nations and highlight the applicability of the method to more than one country. There remain considerable opportunities to analyse indicator outcomes in more detail. A useful starting point would be the country of Iceland. The nation has already been subject to an evaluation by Olafsson et al. (2014), but this study was based on existing environmental indices and, as it acknowledged, did not possess the advantages of a bespoke indicator set relevant to the national context. Broadening the focus a little, it would also be straight-forward to apply the methodology to other countries in the Nordic region. Although Paper I emphasises the importance of not directly comparing countries in terms of outcomes, there remain many common indicators and targets applicable to all five countries. Understanding how and why similar countries are performing better/worse than others can help to inform new policy initiatives and environmental management schemes. There also exists the opportunity to apply the methodology to even wider contexts, such as the European Union or countries outside of Europe. Care should be taken to ensure that the focus group and expert team have considerable knowledge of any national context in which the method is applied.

Further indicator research could also be focused on how to improve data gathering, increasing the regularity of collection and reducing time lags. Even more importantly, there is an urgent need to establish robust indicators for measuring the environmental sustainability of fisheries and soil erosion. The absence of these undermines the comprehensiveness of the methodology in Paper I.

Research in the field of environmental sustainability in a national context need not confine itself to indicators. Equally, policy and decision-makers may wish to gain knowledge concerning a nation's stocks of ecosystem services, analysing these from the producer and consumer perspective across all landscape types. These objectives are currently integrated within the European Union's Biodiversity Strategy to 2020, which includes an overarching objective to halt the loss of biodiversity and degradation of ecosystem services as far as possible. Action 5 of the Biodiversity Strategy requires *"Member states, with the assistance of the Commission, to map and assess the economic value of such services, and promote the integration of these values into accounting and reporting systems at national level by 2020"* (European Commission, 2011). Although a broader concept than biodiversity, the spatial mapping and accounting aims of Action 5 are objectives closely aligned with a strategy for promoting environmental sustainability on a national scale. There are many rationales for mapping ecosystem services. Irrespective of the tier of analysis – local, regional or national, motivations may include examination of synergies and trade-offs between different ecosystem services, estimations of costs and benefits, comparisons of supply with demand, placing a monetary value on biophysical quantities, or prioritization of areas in spatial planning and management (Maes et al., 2012). The use of economic information may help to promote the maintenance of ecosystem integrity via the efficient management of natural resources and the decoupling of environmental pressures from economic growth.

In an Icelandic context, although the nation is not an EU state, there appear to be advantages to commencing the mapping and valuation of ecosystem services in order to contribute to the promotion of environmental sustainability. These include: (a) first, as Papers IV and V have stated, the nation currently has very limited knowledge concerning the type, spatial distribution, temporal scale, and economic value of its ecosystem services; (b) second, in a European context, the nation is highly distinct in terms of its landscape, having been shaped continuously by glacial and volcanic processes; and (c) third, the environmental sustainability of the nation has already been recently appraised in the paper's by Olafsson et al. (2014) and, to a very limited extent, in Paper I.

Various approaches could be adopted by researchers to map Iceland's ecosystem services. The most straight-forward approach might be to derive information on ecosystem services from land-use cover maps (Kienast et al., 2009; Vihervaara et al., 2010). This method is most suitable to larger spatial scales, for areas where the dominant services relate to land use, or where data availability is limited (Maes et al., 2012). Alternative approaches based on the collection of primary data provide considerably greater data accuracy, but such processes are resource intensive with the general exception of provisioning services – for example, timber, fish, or minerals. Often for regulating, supporting and cultural ecosystem services, practitioners have to rely on proxy values for quantification (Maes et al., 2012). The use of value transfer methodologies is another means of translating existing valuation data to a new study area (Brander and Koetse, 2011). They are then linked to supply indicators, either with uniform values or adjusted for spatial variables (Troy and Wilson, 2006). The most advanced approaches involve dynamic process-based ecosystem models (Morales et al., 2005). These utilise ecological production functions to take account of the processes responsible for ecosystem service delivery. These are likely to be the most accurate approaches, especially at the local scale, but are costly in terms of time spent gathering data and knowledge (Maes et al., 2012).

7.6.2 Non-market valuation techniques and ecosystem services from geothermal areas

This thesis has described some of the challenges of conducting non-market valuation techniques specific to the ecosystem services provisioned by geothermal areas. However, the case of clean air represents one regulatory ecosystem service where it may be practicable for researchers to estimate the welfare losses associated with the impacts of developing geothermal power. Hydrogen sulphide gas is a significant component of geothermal steam and is very toxic, with high-concentrations promulgating a range of breathing-related health issues in human beings, including death in the severest cases. In Iceland, the Hellisheiði Power Plant has emitted concentrations of hydrogen sulphide in excess of the World Health Organization's safe limits (Olafsson et al., 2014). An evaluation by Carlsen et al. (2012) concluded that hydrogen sulphide emissions from Hellisheiði were associated with increased dispensing of anti-asthma drugs in nearby Reykjavík. There are two ways in which academics could apply the avoided cost method to evaluate impacts in this context. First, they could research the economic costs of increased purchases of medication in mitigation of expected/experienced symptoms. Care would have to be taken to ensure that additional purchases were related to increased concentrations of hydrogen sulphide in the local atmosphere. Second, and perhaps a more practical option, research could be directed to examine the total economic costs (capital, labour and incidental expenditures) of installing the necessary scrubbing technology in power plants to reduce concentrations to permanently safe levels to human health. Alternatively, researchers could examine the total economic costs of reinjecting hydrogen sulphide, which is an ongoing exploratory research venture conducted by Reykjavík Energy at Hellisheiði.

Another very interesting line of research could follow-on connected to impacts to recreational amenity caused by developing a geothermal power project. From an academic perspective, there are currently no global studies focused on estimating the recreational value of geothermal areas. Although used relatively sporadically, the case studies of Eldvörp and Hverahlíð are clearly associated with some level of recreational value, particularly the former with its range of walking paths, diverse geomorphological features and evidence of human settlement. A travel cost study could be conducted to estimate the value of recreational amenity, albeit it would be challenging due to the relative remoteness of these sites. If researchers wished to estimate the change in consumer surplus associated with developing a power project, then they would need to apply both revealed and stated preference techniques. This would be costly in terms of time and labour resources, but the outcomes could greatly inform the debate concerning impacts to recreational amenity caused by geothermal power projects in Iceland. It might not be the case that the economic value of recreational amenity diminishes, as provision of visitor centres, educational trips and spa facilities might lead to welfare gains.

A holistic academic study of the economic value of ecosystem services remains overdue in a geothermal context. Such a study would present researchers with considerable challenges, but would also be of considerable interest in the general field of economic valuation, particularly connected to issue such as the avoidance of the double-counting of benefits (costs) and the opportunity cost of providing one service in terms of a loss in another.

As Paper II stated, there are also opportunities to further explore opportunities to incorporate economic information into the planning for geothermal power projects. The erection of power lines is the most far-reaching of the environmental impacts caused by a geothermal power project, potentially affecting the scenic amenity and aesthetics of many vistas. No academic publications currently exist connected to the economic value of the environmental impacts of power lines connected to geothermal projects. Choice experiments could be set up to survey preferences and willingness to pay for a variety of permutations, including the laying of cables underground.

Finally, Paper III's thematic review of ecosystem services particular to geothermal areas is specific to high-temperature fields, and so too are the contingent valuation studies reported in Paper IV. High-temperature fields are generally considered to be the most severe in terms of environmental impacts due to their use in electricity generation. However, no studies have yet occurred in relation to the ecosystem services impacts associated with the development of low-temperature fields for usage in hot water and district heating systems. This is a potentially interesting avenue of research given the spatial scale of some district heating systems fuelled by geothermal energy, such as Reykjavík's.

7.7 Conclusion

The concept of development has often been assimilated into that of economic growth. Therefore, the national tools available to monitor economic growth are limited to analysing various development components and their economic consequences. These tools are not suitable for analysing causes or interrelationships connected to the environmental implications of national economic activity. Given the importance of the environment to national economic well-being – as an input in terms of raw materials for product generation, as a waste assimilator – fostering greater understanding of the sustainability of the environment is crucial to ensuring the long-term flourishing capacities of the economy and its population. This thesis has advanced a methodology for the selection of environmental sustainability indicators suitable to the nation-state context. The chosen set can provide decision-makers with the information to monitor and measure changes in the environmental state. Drawing upon the case study examples of Iceland and Norway, the methodology helps to build a consensus on what environmental sustainability is in a quantitative sense, advocates the use of differentiated targets specific to the national context, and sets out the graphical reporting tools necessary to monitor performance over time.

Environmental sustainability is a concept based on a notion of ecosystem services. In order to continue to enjoy the services provisioned by natural capital, human beings must continue to live within the limitations of the biophysical environment. In Iceland, the development of energy systems fuelled by renewable energy – particularly geothermal energy in recent decades – has generally been considered as advancing human well-being. This assertion may well be correct, however the welfare implications of impacts to the provisioning of ecosystem services have, until this research, not been evaluated. In this thesis, the first thematic review of ecosystem service impacts was conducted particular to geothermal areas. Following this, two contingent valuation studies were undertaken, estimating the economic value of the environmental impacts associated with developing two of Iceland's geothermal fields: Eldvörp and Hverahlíð. The use of economic evaluations of environmental impacts within cost-benefit analysis has been demanded by the OECD in relation to Icelandic energy projects. Thus, although the valuation outcomes will be of considerable interest to international academics and domestic policy and decision-makers, this thesis has added practical value through its delineation of a methodology which can satisfy the OECD's clarion call. Additionally, given the scale of the costs revealed in this thesis and the likelihood of Iceland expanding its utilisation of high-temperature geothermal resources in the next few years, accounting for the economic value of environmental impacts should become part of the basis for determining license approvals.

There remains a pressing need for Iceland to gain knowledge of the economic value of its ecosystem services across all of its diverse landscape types. The contingent valuation study of Heiðmörk, drafted in Paper V, represents an estimate of the economic value of developing one of Iceland's most popular urban parks. Future research should particularly focus not only on the practical use of the environmental sustainability indicators, but also the establishment of a framework for the spatial mapping and economic valuation of all of Iceland's ecosystem services, both from the perspective of the producer and consumer.

7.8 References

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