Energy for Sustainable Development 40 (2017) 126–138

Contents lists available at ScienceDirect

Energy for Sustainable Development

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

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ARTICLE INFO

Article history:
Received 7 December 2016
Revised 18 July 2017
Accepted 19 July 2017
Available online 2 August 2017

Keywords:
Decision-making
Valuation
Geothermal energy
Environmental impacts
Ecosystem services

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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http://dx.doi.org/10.1016/j.esd.2017.07.007
0973-0826/

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

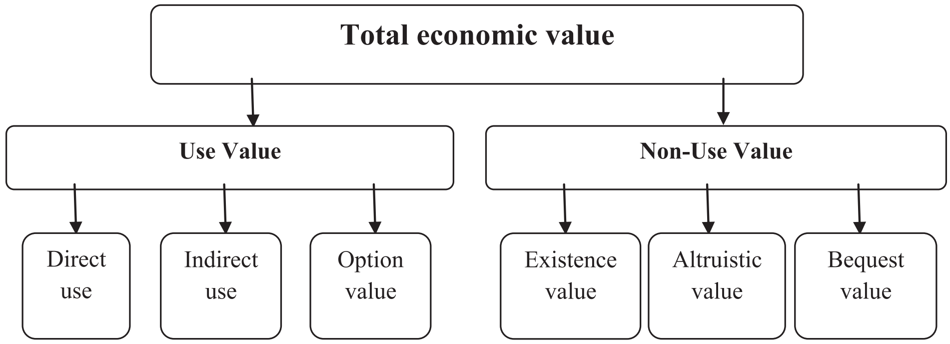

Fig. 1. Total economic value framework.

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 reinjection (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.

Acknowledgements

This paper has been funded by GEORG (Grant no. 11-04-002), the geothermal research group in Iceland, and the Icelandic Research Council.

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