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Abstract

This paper presents the first study in the academic literature to explore the various stages in the formation of geothermal ES and their interactions between the biosphere and anthroposphere. This is achieved through the development of the first ES cascade model in the academic literature specific to geothermal ES, which integrates the four main stages of co-production: value attribution, mobilisation of ES potential, value appropriation, and commercialisation. In so doing, conceptual understanding of human-environment relationships and processes in the context of geothermal ES are deepened. Examples from the academic and grey literature demonstrate that realisation of the full spectrum of benefits from geothermal areas often demands the mobilisation of various forms of physical capital. Reaping the benefits of provisioning ES, such as heat and minerals, or formal recreational experiences, such as geothermal spas, necessitates human interventions. Opportunities of likely value have to be attributed, with resources being mobilised in order to plan and research prospectivity, then benefits appropriated with a view to their commercialisation. Large-scale, industrial projects, especially geothermal power plants in high enthalpy fields, also constitute an overlap between anthropogenic and ecological systems, often leading to ES trade-offs, especially due to visual and noise impacts on the surroundings. Depending on the sociocultural context, multiple and conflicting value domains may be impacted by such ventures, justifying the adoption of a pluralist approach to valuation and use of integrated decision-support platforms to aid decision-makers.

Keywords: co-production; geothermal energy; ecosystem services; trade-offs; values

1. Introduction

The concept of co-production has been considered in a broad array of contexts. In the social sciences, Ostrom (1996) discussed the concept in the context of public administration, whereby services, such as education, were 'co-provided' by people who did not belong to the same institution or organisation. More recently, co-production has received increasing attention in the ecosystem services (ES) literature (Montana, 2019; Rademacher et al., 2019; Malinauskaite et al., 2020), with studies often involving a focus on interactions between human and ecological systems (Fischer & Eastwood, 2016; Potschin & Haines-Young, 2016; Spangenberg et al., 2014). The interdisciplinary and transdisciplinary character of ES analysis has been reinforced through co-production analysis, with emphasis placed and greater understanding formed concerning the linkages between biophysical structures and processes to human values, benefits and well-being (Potschin & Haines-Young, 2016). The concept of co-production also provides a useful apparatus for understanding the contributions of different forms of capital – human, social, manufactured and financial – to the supply of ES and receipt of human wellbeing benefits (Outeiro et al., 2017; Palomo et al., 2016).

A relatively limited body of research exists focused on ES in the context of energy production, despite the obvious links of the energy sector to positive impacts on human well-being, especially through energy services such as energy provision, energy security and potentially the mitigation of climate change (Kalt et al., 2019). The study by Hastik et al. (2015) began to fill this void by applying the Common International Classification of Ecosystem Services (CICES) framework to conduct an evaluation of the most frequent trade-offs involved in the development of biomass production, wind power, hydro power and solar photovoltaics. This work was further advanced through an analysis of common ES trade-offs and enhancements pertaining to the development of power projects in geothermal areas (Cook et al., 2017), and consideration of how pluralist valuation of such impacts could be applied to inform decision-making (Cook et al., 2019). On an international scale, the ES impacts of developing geothermal power could be considerable in the coming years, not least due to the increased global focus on harnessing high enthalpy geothermal fields for electricity production (Okamoto, et al., 2019). Worldwide, 14.3 gigawatts (GW) of geothermal power capacity had been installed by 2018, and it currently provides a sizeable share of national electricity generation in Kenya (40%), Iceland (30%), El Salvador (25%) and New Zealand (18%) (BP, 2019).

Co-production processes linked to geothermal ES have yet to be explored in the academic literature, however, the thematic studies by Cook et al. (2017) and Cook et al. (2019) provided evidence of ES trade-offs and enhancements in the context of geothermal areas through the development of power projects. The scope of these two works did not include an exploration of the various interactions between ecological and socio-economic systems, and their underlying physical and cognitive processes, which will be explored in this paper, adding depth to understanding of (a) the formation of ES specific to geothermal areas, and (b), the potential ES trade-offs and benefits of developing geothermal power ventures. Additionally, much of ES research to date has focused on awareness raising, with a view to increasing the likelihood of decision-makers choosing to conserve resources if the public benefits of conservation outweigh the costs (Birkhofer et al., 2015; Zheng et al., 2016). Based on the evidence that co-production of ES is associated with ES trade-offs and enhancements derived from human influences on geothermal areas, such a perspective can also assist in identifying policy and management interventions aimed at minimising the extent of trade-offs and maximising positive impacts to human well-being. Due to its systematic analysis of interactions between ecological and human systems, and their various natural and non-natural inputs, it thus goes beyond the level of investigation typically involved in Environmental Impact Assessments or Life-Cycle Analysis relating to geothermal power, or the energy sector in general.

The main aim of this paper is thus to contribute to a greater understanding of the various human-environment interactions in geothermal areas, including those linked to power projects, recreation and educational experiences. This will be performed via analysis of co-production processes through the application of the five-stage ES cascade model of Malinauskaite et al. (2020). The stages are illustrated through examples from the academic and grey literature. This paper is structured as follows. Section 2 provides background information concerning the ES cascade model, various features of co-production processes that will be applied in this paper, and outlines the model of Malinauskaite et al. (2020). Section 3 provides a brief overview of the main environmental characteristics of undeveloped geothermal areas, before providing the first comprehensive CICES classification of geothermal ES. Section 4 articulates the cascade model of Malinauskaite et al. (2020) with respect to geothermal ES and discusses the applicability of core features of ES co-production processes: value attribution, mobilisation of potential, appropriation, and commercialisation. Section 5 discusses the valuation and decision-making implications of the analysis, in addition to reflecting on the limitations of the ES cascade model. Section 6 provides a brief conclusion and reflection on opportunities for future research.

2 Theoretical overview and framework

2.1 The ES cascade model

The ES cascade model identifies five main stages involved in the emergence of ES, including supply and demand-side occurrences (Haines-Young & Potschin, 2010; Haines-Young & Potschin, 2018; Martín-López et al., 2014; Potschin & Haines-Young, 2016). As illustrated in Figure 1, these are biodiversity, functions, ES, human wellbeing, and value.

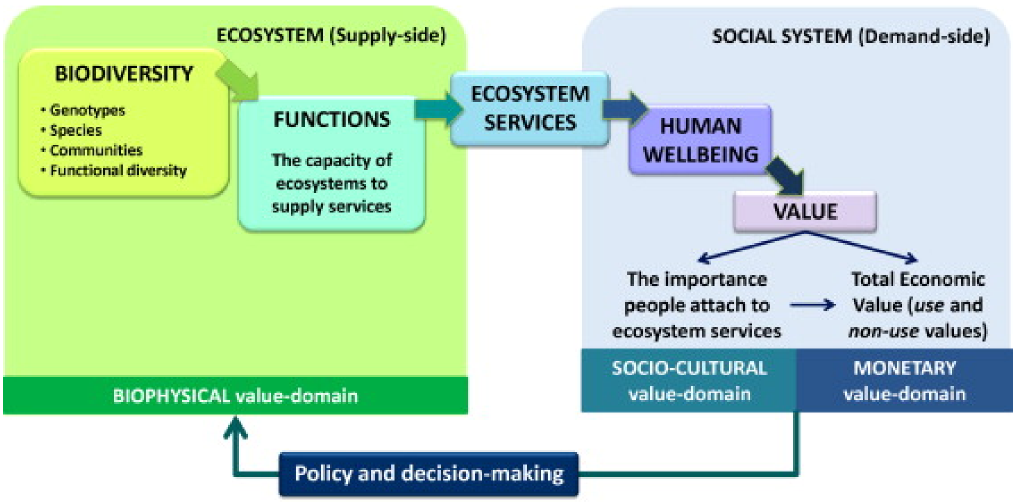

Figure 1. Conceptual framework of ES cascade model and value domains embedded in social-ecological systems. [1]

[1] Sourced from Haines-Young and Potschin (2010) and Martín-López et al. (2014).

Biodiversity and related functions and processes are located on the supply-side of the flow diagram, and amount to the ecological infrastructure which is necessary for the formation of ES (Haines-Young & Potschin, 2010; 2018). These then contribute to human wellbeing in various ways on the demand-side. The model demonstrates overlap between the ecosystem on the supply-side and human wellbeing and values on the demand side, with ES located at the intersection of the two (Malinauskaite et al., 2020). Two value domains are recognised on the demand-side in relation to human wellbeing: monetary and socio-cultural (Castro et al., 2014; Martín-López et al., 2014). These imply a need for valuation to inform policy and decision-making, management endeavours and influences which generate a feedback loop from the social system on the demand-side back to the ecosystem on the supply-side (Malinauskaite et al., 2020).

Critics of the ES cascade model in Figure 1 have contended that it pays insufficient attention to underlying social processes and human capital inputs (Fischer & Eastwood, 2016; Outeiro et al., 2017; Spangenberg et al., 2014). Evidently, each stage of the ES cascade model requires natural capital, but also frequently physical (human and built) capital inputs in order to create a transition to further stages in the cascade (Malinauskaite et al., 2020).

2.2 Co-production processes

Spangenberg et al. (2014) focused on overcoming the criticisms of the model by identifying social processes and human agency at each stage in the ES cascade, enabling useful insights to be gleaned on co-production processes for those ES influenced by human involvement. Two broad types of ES co-production have been identified by Palomo et al. (2016): physical and cognitive. Malinauskaite et al. (2020) consider physical co-production processes to relate to measurable changes in material ES flows on the supply-side, while cognitive co-production processes involve the perceptions of human beings concerning the benefits of ES, either via direct, indirect or remote interactions with the ecosystem.

Four co-production processes were identified by Spangenberg et al. (2014), which are briefly defined in Table 2.1.

Table 2.1. Co-production processes in the ES cascade.

Co-production Process	Definition
Value attribution	"Characterised as an intellectual act defining an ecosystem service potential, as a potential supply for an assumed societal (and thus group and culture specific) demand" (Spangenberg et al., 2014, p. 25)
Mobilisation of potential	"Anthropogenically defined and produced, the results of socio-technical systems activating the potentials offered by nature's functions" (Spangenberg, 2014, p. 25)
Appropriation	"The transformation, processing and /or providing of the services to generate ecosystem benefits, again requiring investments of time, work and resources, and money as a means to make them available" (Braat and de Groot, 2012, p.8)
Commercialisation	"Occurs when appropriated ES are sold in markets, i.e. when those who mobilise and/or appropriate ES decide to exchange at least a part of them for money or other goods" (Malinauskaite et al., 2020, p.6)

2.3 Expanded ES cascade model including co-production processes

The recent publication by Malinauskaite et al. (2020) integrated the various co-production processes of Spangenberg et al. (2014) to build on Figure 1 and create an expanded whale ES model. Although illustrated and analysed specifically with respect to the nascent topic of whale ES, the model of Malinauskaite et al. (2020) (Figure 2) has general applicability to any ecosystem context. Differentiating subtly in terminology from the model in Figure 1, Malinauskaite et al. (2020) refer to the supply-side as the biosphere and the demand-side as the anthroposphere. Overlap between the biosphere and anthroposphere occurs at the appropriation stage of co-production. In line with Haines-Young and Potschin (2010) and Martín-López et al. (2014), the two value domains of monetary and sociocultural receive valuation in order to inform policy and decision-making. Where the monetary valuation domain applies, the benefits are use, either direct or indirect, these can be commercialised via markets, resulting in an exchange value informative to policy and decision-making.

In the model of Malinauskaite et al. (2020), regulating and maintenance ES are considered to link directly from the ecosystem and its biophysical structure, processes and functions (ecological infrastructure) to the receipt of human wellbeing benefits on the demand-side. In other words, there is no supply-side role for co-production specific to this type of ES, since regulating and maintenance services imply indirect use value and do not require additional sourcing effort by humans. The model recognises that most whale ES (except the regulating and maintenance type) involve active human involvement, either physical or cognitive. In contrast to the regulating and maintenance type of ES, provisioning ES will involve direct interactions between human beings and an ecosystem, while cultural ES will often concern direct or indirect interactions between human beings and an ecosystem, in addition to value attribution connected to its existence.

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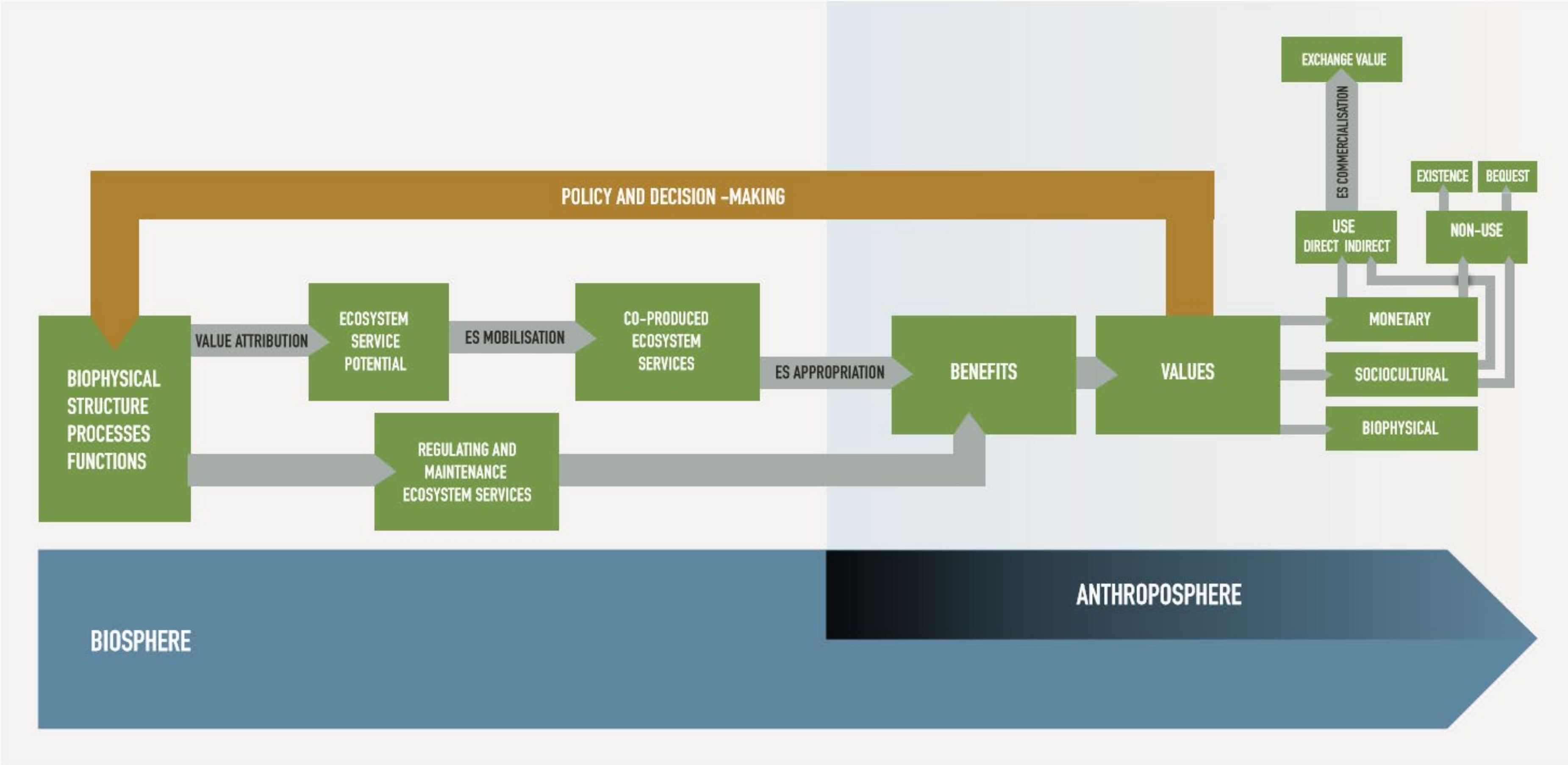

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212 **Figure 2. ES cascade model including co-production processes.**[2]

[2] Sourced from Malinauskaite et al. (2020)

3 Phenomena and ES of geothermal areas

3.1 Characteristics and environmental features of geothermal areas

Features of geothermal areas vary from location to location, but they all include a range of geophysical, geochemical, geomorphological and biological manifestations at the surface level, stimulated by thermal energy stored in rocks deep in the earth and conveyed to the surface by water, steam and other mineral-heavy fluids (Dickie & Luketina, 2005). The various features are discussed in Cook et al. (2017) and summarised in Table 3.1.

Table 3.1. Geothermal phenomena.

Features of geothermal area	**Description**
Discharges	Steam, gases, water and other minerals.
Depositions	Mineral accumulations, such as silica.
Time dependent behaviour	Geysers, fumaroles, mud flows and hydrothermal eruptions.
Land surface changes	Heated or chemically altered surfaces.
Geodiversity	Unusual and distinctive land formations and geomorphological features such as craters, sinter terraces and caves.
Rare terrestrial and aquatic ecosystems	Unique or rare forms of flora (mosses, ferns, fungi etc.), fauna (especially migratory bird species), genetic materials (enzymes often used as amplifiers of DNA fragments in forensics), algae (used in biofuels production), bacteria (used in industrial applications for biodegradation), and microbes.

3.2 ES of geothermal areas

The publication of Cook et al. (2017) outlined an inventory of common ES specific to geothermal areas[3], grouping these according to the three types of ES denoted by CICES: provisioning, regulating and maintenance, and cultural. However, a comprehensive CICES classification was not presented by the authors, which involves the identification of sections (types), divisions, groups, classes, class types and services. This paper presents (Table 3.2) a detailed CICES classification based on the latest version of the technical guidance authored by Haines-Young & Potschin (2018).

[3] For detailed indformation concerning each of the geothermal ES discussed in this paper, please refer to the study by Cook et al. (2017). Note that the inventory was not designed to be an exhaustive analysis of all of the ES that might relate to geothermal areas.

Table 3.2. CICES classification of geothermal ES.[4]

Section	Division	Group	Class	Class type	Service
Provisioning (abiotic)	Non-aqueous natural abiotic system outputs	Non-mineral substances or ecosystem properties used for nutrition, materials or energy	Geothermal	By amount, type, source	Genetic resources
Provisioning (abiotic)	Aqueous natural abiotic system outputs	Non-mineral substances or ecosystem properties used for nutrition, materials or energy	Geothermal	By amount, type, source	Geothermal energy
Provisioning (abiotic)	Non-aqueous natural abiotic system outputs	Mineral substances used for nutrition, materials or energy	Mineral substances used for nutrition or material purposes	By amount, type, source	Mineral resources
Regulation and maintenance (abiotic)	Transformation of biochemical or physical inputs to ecosystems	Mediation of wastes or toxic substances of anthropogenic origin by living processes	Filtration, sequestration, storage, accumulation by micro-organisms, algae, plants and animals	By type of living system or by water or substance type	Water purification
Regulation and maintenance (abiotic)	Transformation of biochemical or physical inputs to ecosystems	Mediation of wastes or toxic substances of anthropogenic origin by living processes	Bio-remediation by micro-organisms, alga, plants, and animals	By type of living system or by waste or substance type	Waste treatment
Regulation and maintenance (abiotic)	Regulation of physical, chemical, biological conditions	Atmospheric composition or conditions	Regulation of chemical composition of the atmosphere	Contribution of amount of living system to amount, concentration or climatic parameter	Air quality regulation
Cultural (abiotic)	Direct, in-situ and outdoor interactions with natural physical systems that depend on presence in the environmental setting	Physical and experiential interactions with natural abiotic components of the environment	Natural, abiotic characteristics of nature that enable active or passive physical and experiential interactions	Amount by type	Recreation
Cultural (abiotic)	Indirect, remote, often indoor interactions[5] with	Spiritual, symbolic and other interactions with	Natural, abiotic characteristics of nature	Amount by type	Spiritual enrichment

[4] Note that version 5.1 of CICES does not currently list provisioning (abiotic) resources for the division of genetic resources or cultural (abiotic) for inspiration or education, and therefore the authors have assumed how such resources would be bracketed if they were incorporated.
[5] Note that spiritual enrichment may also take place outdoors and 'in-situ'

Section	Division	Group	Class	Class type	Service
	physical systems that do not require presence in the environmental setting	the abiotic components of the natural environment	that enable spiritual, symbolic and other interactions		
Cultural (abiotic)	Direct, in-situ and outdoor interactions with ecosystems that depend on presence in the environmental setting	Intellectual and representative interactions with natural environment	Characteristics of ecosystems that enable aesthetic experiences	By type of ecosystem or environmental setting	Aesthetics
Cultural (abiotic)	Direct, in-situ and outdoor interactions with ecosystems that depend on presence in the environmental setting	Intellectual and representative interactions with natural environment	Characteristics of ecosystems that enable inspirational experiences	By type of ecosystem or environmental setting	Inspiration
Cultural (abiotic)	Direct, in-situ and outdoor interactions with ecosystems that depend on presence in the environmental setting	Intellectual and representative interactions with natural environment	Characteristics of ecosystems that enable educational experiences	By type of ecosystem or environmental setting	Education
Cultural (abiotic)	Direct, in-situ and outdoor interactions with ecosystems that depend on presence in the environmental setting	Intellectual and representative interactions with natural environment	Characteristics of ecosystems that are resonant in terms of culture or heritage	By type of ecosystem or environmental setting	Archaeological heritage
Cultural (abiotic)	Indirect, remote, often indoor interactions with physical systems that do not require presence in the environmental setting	Other abiotic characteristics that have a non-use value	Natural, abiotic characteristics or features of nature that have either an existence or bequest value	Amount by type	Existence and bequest value

4 Geothermal ES cascade model and analysis of co-production processes

This section links the theoretical framework in Figure 2 to the list of services in Table 3.2. Its analysis is split into two parts. The first briefly examines geothermal examples in relation to the five stages in the ES cascade model. The second part specifically analyses co-production processes concerning geothermal ES and the common ES trade-offs of developing geothermal power projects.

4.1 Geothermal ES – cascade stages

4.1.1 Biophysical structure / process / function

The combination of heat, steam, gases (especially hydrogen sulphide) and minerals (especially silica and lithium) sourced from the mantle of the earth lead to a diverse array of geochemical and geophysical surface manifestations (Benavente et al., 2016; Ouali et al., 2011). The underlying geochemical and geophysical reactions, where manifested at the surface level as ecosystem interactions, provide the ecological processes and functions necessary for the supply of ES. These include depositions of provisioning ES, such as minerals and genetic resources, underlying functions supporting regulating and maintenance ES, and various geophysical and aesthetic effects underpinning cognitive appreciation and linked to several cultural ES.

4.1.2 Ecosystem service potential (ESP)

In this stage of the ES cascade, the ES of potential value to human wellbeing are identified by actors with the resources and capabilities to secure their utilisation, especially provisioned ‘goods’, such as minerals and heat, and recreation. This is particularly likely to be the case where provisioning and cultural services are deemed to be of commercial value to the industrial and business sectors. Bloomquist (2006) analysed the economic benefits of co-production of minerals from geothermal brines, including silica, zinc, manganese, lithium and other rare earth metals. In particular, extraction of silica was found to be associated with co-benefits in geothermal power projects as it reduced scaling problems, facilitating additional power production. Silica has been widely used by the pharmaceutical and cosmetic industry as an ingredient in skin creams targeted at the treatment of conditions such as eczema and anti-ageing (Einarsson et al., 2009). In addition, skin treatments involving silica and algae, such as mud masks and facials, are an increasingly popular add-on experience at geothermal spas (Blue Lagoon, n.d.).

Peaceful surroundings and the presence of multi-coloured and geo-diverse environments in geothermal areas generate rare aesthetics, which are attractive to people for their recreational benefits (Cook et al., 2019; Shortall et al., 2015). Often these recreational benefits are somewhat informal, such as bathing in hot springs or enjoying being in a distinct and evolving landscape (Dowling 2013; Borović and Marković, 2015; Liu and Chen, 2015). However, commercial actors often identify opportunities to develop formal recreational experiences, securing long-term economic benefits. The identification of potential geothermal spa sites by developers, planning agencies and tourism management bodies represents an example of the ESP stage in the ES cascade. Yellowstone National Park can be considered an example where ESP has not only been recognised by decision-makers, but it has then been actualised throughout the ES cascade, with benefits captured through formal exchange mechanisms. Public access to the Old Faithful geyser in Yellowstone National Park requires a fee to be paid (Yellowstone National Park, n.d.). This is in contrast to some other famous geothermal sites around the world, such as Geysir in Iceland, which are free to access yet they still constitute formal recreational areas partially managed by public bodies.

4.1.3 Co-produced ecosystem services

Many geothermal ES require active human involvement – thus, co-production – in order to secure benefits, either economic or sociocultural. From the utilisation of geothermal resources for various energy services to tourism initiatives linked to geothermal areas, these require human input throughout the design, construction and operational phases of the venture (Kurek et al., 2020). Equally, the extraction of provisioning ES from geothermal brine is often a complex process, necessitating specific expertise and technological capacity (Sugita et al., 1998; Ueda et al., 2003). The specific co-production processes linked to these examples are explored in more detail in the mobilisation and appropriation parts of section 4.2.

4.1.4 Benefits

Figure 2 illustrates two ways in which the benefits of ES are received by human beings, either via co-production or indirect of human involvement in the form of vicarious consumption (Malinauskaite et al., 2020). The latter relate to regulating and maintenance ES, and non-consumptive benefits which imply indirect use value. The benefits of water purification, waste treatment and air quality regulation in geothermal areas have been lightly studied in the academic and grey literature (Cook et al., 2017), however, the health impacts ('ecosystem disservices') of changes in emissions caused by geothermal utilisation have been explored to some extent. Although there is currently no evidence to suggest that exposure to long-term ambient concentrations of hydrogen sulphide emissions may result in health effects (Bates et al., 2015), even short-term exposure to high concentrations of greater than 200 ppm can be acutely toxic and potentially life threatening (Durand and Wilson, 2006).

Other benefits of geothermal ES generally involve direct physical and/or cognitive interactions between the biosphere and anthroposphere. This is particularly the case in relation to cultural ES, with the exception of benefits linked to non-use value which can only be cognitive. In addition to their contribution to the quality of recreation at a geothermal site, the cultural ES of aesthetics, inspiration and archaeological heritage all constitute benefits in their own right. Geothermal areas have been cited as an inspiration for artists due to their aesthetically pleasing qualities, which partly relate to their unique geo-diversity (Cook et al., 2017; Cook et al., 2019; Gray, 2012). Although typically sparsely populated in the modern era, geothermal areas are also sometimes the location of important archaeological remains of heritage value (Borović & Marković, 2015). The benefits of spiritual enrichment sourced from geothermal areas can be formed individually or collectively, depending on the context. Examples include the spiritual beliefs, practices and rituals of the Maori culture in New Zealand (Shortall et al., 2015; Zeppel, 1997). Other indigenous groups, such as the Maasai in Kenya, have associated themselves with notions of the sacred value of geothermally active land (Lund, 2006).

4.1.5 Value

Figure 2 illustrates three value domains of biophysical, sociocultural and monetary. Two of these are then *valued*: sociocultural and monetary. The biophysical domain involves the ecological functions and processes of geothermal areas, necessary for the supply of either regulating and maintenance or co-produced ES. These ES are translated into sociocultural and monetary values using appropriate valuation techniques (Gómez-Baggethun & Barton, 2013; Jax et al., 2013). Generally, the provisioning of ES from geothermal areas relates to the monetary value domain, and can thus be valued using economic information via techniques from the environmental economist's toolkit, such as replacement cost, the production function approach, market pricing and contingent valuation (Cook et al., 2017).

Different and multiple values[6] may apply to geothermal areas depending on their locality and the cultural and socio-economic context. Other than recreation, cultural ES sourced from geothermal areas are often ill-suited to commercialisation and thus relate to the sociocultural value domain (Cook et al., 2019). Spiritual enrichment is perhaps the most obvious example. This ES is often formed collectively rather than individually among a society based on traditional knowledge, and established following interactions between formal and informal governance institutions (Martín-López et al., 2014). Particularly where symbolic resonance or the sacredness of land is relevant, monetary metrics of value, such as willingness to pay, would be an inappropriate form of valuation (Cook et al., 2017; Cook et al., 2019; Cooper, 2009).

4.2 Co-production processes and ES impacts involving power projects

4.2.1 Value attribution

Geothermal minerals can often be easily identified and their abundance determined via their presence in surface manifestations, such as fumaroles and hot springs. Sometimes their presence is concealed or fossilised and their identification requires advanced analytical approaches, which can include the use of approaches such as Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Hyperion datasets (Abubakar et al., 2017). At an early stage, developers will need to make a decision concerning the market potential of the various minerals associated with a geothermal area. This evaluation is performed mainly based on perceived abundance, the historical costs of extraction and anticipated future price. Often geothermal minerals will be of very low concentrations, and sometimes minerals, historically chlorides and sulphides, will already be sufficiently abundant on the market because of oversupply, leading to low and unappealing prices (Blake, 1974). Concentrations of minerals and thus the economic potential of mineral extraction can vary greatly from site to site, even within nations. A geochemical study of 30 geothermal areas in Iceland, including 1,650 samples, found measured concentrations of silica in geothermal fluids ranging from 10 to 1,000 ppm, with the highest values found at the sites of some of the nation's main geothermal power plants: Krafla, Hellisheiði and Nesjavellir (Camacho, 2017).

With regards to identifying the commercial potential of recreational activities at geothermal areas, the growth in geothermal spa and wellness facilities worldwide is one of the features of 'geo-tourism' (Erfurt-Cooper & Cooper, 2009). Geothermal waters are especially popular locations for spa facilities as they are renowned for their health and spiritual benefits (Smith & Puczko, 2008). In terms of value attribution, spa developers in Iceland have typically identified locations that have a particular commercial appeal and uniqueness (Cook et al., 2019). In addition to satisfying temperature criteria and the facilities being located close to or on major roads used by tourists, the spas may be organic, historic and natural (e.g. the Secret Lagoon in Flúðir), or modern and linked to outflows from power plants (e.g. the Blue Lagoon at Svartsengi or Mývatn Nature Baths) (Chapman, 2017).

4.2.2 Mobilisation of ESP

In the context of provisioning ES, having identified possible areas of value, the process of exploration, further planning and evidence sourcing of likely economic prospectivity constitutes the mobilisation of ESP. This may necessitate a considerable funding commitment on the part of the developer and/or the need for external sources of finance. A $4 million fund by the US Department of Energy exemplified the importance of financing to support the mobilisation of research into the presence of rare-earth minerals and metals dissolved in high

[6] And thus different valuation languages. See Cook et al. (2017) for a detailed assessment of the likely valuation techniques, either monetary (non-market) or non-monetary that are likely to apply to each geothermal ES.

enthalpy geothermal fluids. Emphasis was placed in the funding call on quantifying the potential for the recovery of these critical materials, which could make an important contribution as components in many low-emission technologies, including solar panels, electric vehicles and energy efficient lighting (US Department of Energy, 2016). Other recent research in the US has explored the economic potential of recovering critical and strategic minerals from geothermal brine. A nation-wide feasibility study by Neupane & Wendt (2017) determined that several mineral commodities were present in high enough concentrations and flow rates to be economically recovered. Moreover, suitable and already tested mineral-specific and multi-minerals bench-scale extraction technologies were deemed ready for deployment

The planning and initiation phase for spa facilities amounts to the main mobilisation aspect with respect to recreation. Often this can be a lengthy and complicated process, one that has been exemplified in recent times by the construction of spa facilities linked to the Olkaria high enthalpy geothermal field in Kenya (Mangi, 2018). The idea – value attribution – to develop a geothermal spa at Olkaria was first initiated in 2008. Mobilisation then took place via research into the suitability of the geothermal brine and its flow for bathing and then the design of facilities, a three-year process before appropriation took place in the form of construction activities (Mangi, 2015).

Mobilisation of potential in relation to geothermal power plants involves a capital intensive process, often amounting to more than 50% of the total cost of any electricity-generating project (Parada, 2016). The construction of roads to the site and the drilling of exploratory boreholes is a noisy process, potentially diminishing the aesthetic quality of the locality and harming the regulating and maintenance ES of clean air through e.g. hydrogen sulphide emissions (Apostol et al., 2016). Sometimes land-use conflicts can occur when power plants are proposed due to the value incommensurability of economic development versus deep and resonant sociocultural traditions of indigenous peoples. This is the case with American Indian land, which comprises around 5% of the total land area but holds close to 10% of its energy resources (Cook et al., 2019; Farhar and Dunlevy, 2003). These indigenous peoples define themselves and gain spiritual enrichment through their connection to the land, which many regard as their ancestral right (Farhar, 2002; Lund, 2006). Similar land-use conflicts with the development of geothermal power have been in evidence in relation to the perceived spiritual entitlements of the Maori peoples in New Zealand (Hikuroa et al., 2010; Kelly, 2011) and the Maasai tribes of Kenya (Mwanza, 2018).

4.2.3 ES appropriation

With the potential benefits of geothermal ES identified with reasonable confidence following the mobilisation stage, appropriation involves the harnessing and deployment of the resources necessary to actualise commercial benefits. Modern and technically feasible options for mineral extraction from geothermal brine include lamellar filtration, which differs from traditional filtration approaches by overcoming the problem of scaling (Borrmann, et al., 2019). Additionally, with respect to geothermal power projects, this stage involves the developer transitioning from exploratory to production-based activities, including the drilling of production wells and construction of plant infrastructure.

The development of the recreational spa at Olkaria in Kenya, located within the Hells Gate National Park, involved a construction process which took place between April 2011 and July 2013. This involved collaboration between multiple disciplines in order to realise the venture, including civil engineers, architects and specialist design consultancies (Mangi, 2015). As the mobilisation of physical capital progressed, the designers opted to expand the size of the largest lagoon from 1,500 m^3 to 3,500 m^3 and added an administration block containing changing rooms, restaurant and an exhibition room. These facilities supplemented the planned conference facility, sauna, steam bath, cable car, children's park and picnic area, which were developed as per the initial plans (Mangi, 2015). A similar construction duration was associated with the Blue Lagoon spa in Iceland between 1992 and 1994, but in this case expansion of the lagoon and visitor facilities took place after the commerciality of the venture had been realised over a period of two decades. The original lagoon was sized to approximately 5,000 m^3 and facilities included the brine flow system, a psoriasis treatment centre, small visitor centre, shop and restaurant. More recently, starting in 2016 and completed in 2018, the lagoon was expanded in size by around 3,000 m^3 and a five-star hotel was constructed (Blue Lagoon, n.d.). The second-phase of development occurred in tandem with the growth of the tourism industry in Iceland, offering evidence that, in the case of recreation at least, the process of value attribution, mobilisation of ESP and ES appropriation is not one single flow, but often iterative as reinvestment opportunities emerge and new ideas for commercial expansion ideas are cultivated.

Utilisation of low-enthalpy geothermal fields for district heating or development of closed-loop binary geothermal power plants often involves the drilling of additional boreholes, erection of plant facilities and construction of the pipe network. Construction of power plant infrastructure linked to high enthalpy fields, including the plant facilities and cooling towers, and the steam-gathering system, is a more capital-intensive process in comparison to utilisation involving low-enthalpy fields (Parada, 2016). Although perhaps a greater array of ES trade-offs are associated with the operations phase (the commercialisation stage in co-production theory), a number of impacts may occur. Many of these will include impacts that were equally observable during exploration activities in the mobilisation stage of co-production, such as noise, visual effects and a deterioration in local air quality (Apostol et al., 2016).

4.2.4 ES commercialisation

ES commercialisation amounts to the operations and sales phase linked to geothermal ES. Examples include sales of minerals, heat to individuals and businesses, and tickets exchanged with tourists in relation to recreational experiences, all of which involve exchange values via market transactions. There is also an increasing drive to maximise economic benefits, utilising all resource streams through cascading use of geothermal energy and in line with the principles of the circular economy. This can include not only the utilisation of minerals and direct uses of the thermal resource but also indirect harnessing, such as use of waste heat for snow melting or in greenhouses, tourist and educational centres, fish farming, factories, spas and swimming pools (Ogola et al., 2012; Yousefi et al., 2019).

Commercialisation, through the instalment of physical infrastructure, may entail ES trade-offs and thus disservices in terms of the quality of the recreational experience in a geothermal area and/or appreciation of its aesthetics. Equally, geothermal power projects in high enthalpy geothermal areas constitute large-scale human interventions and commercialisation, leading to various location-specific trade-offs and impacts to the ES of geothermal areas. In particular, Brophy (1997) and Cook et al. (2017) discussed how noise emissions and visual blight caused during the construction, operation and decommissioning phases of geothermal power plants can contribute to negative impacts to the aesthetics of surrounding landscapes, potentially leading to trade-offs in terms of the quality of the recreational experience. These were also the findings of a cultural impact study by Edelstein and Kleese (1995), which investigated the reasons for native Hawaiian opposition to geothermal power projects. Although perhaps it seems likely that the quality of the recreational experience will diminish due to the development of a geothermal power project, there are examples where cascading uses of geothermal resources might have increased recreational benefits in certain areas, as Iceland's Blue Lagoon and Kenya's Olkaria spas may indicate. Formed in 1976 from the waste waters of the Svartsengi Power Plant, the Blue Lagoon has frequently attracted around 1 million tourists per annum who are keen to relax in its waters (Blue Lagoon, n.d.).

The commercial operations of geothermal power plants have the potential to undermine the quality and quantity of ES in geothermal areas, including causing damage to human health through ecosystem disservices. Some of the trade-offs and impacts may also occur during exploration and construction, and most can be mitigated using current technologies. Although there is no current evidence to suggest harm to human health following long-term exposure to ambient concentrations (Bates et al., 2015), hydrogen sulphide emissions can increase considerably during the operations phase of a power plant, potentially creating local concentrations that have been proven to be harmful to human health via eye irritation and breathing-related ailments (Ermak et al., 1980). Other pollutant incidences potentially occurring during a plant's operational phase include the release of acidic/alkaline effluent into local watercourses, or wastewater flows inclusive of chlorides, sulphides, or dissolved toxic chemicals (Shortall et al., 2015). Additionally, heavy metal water pollution from geothermal power plants has been reported, with production at the Wairakei Power Plant in New Zealand leading to arsenic levels in the Waikato River to more than double, exceeding safe drinking water standards (Ray, 2001). Where geothermal developments take place in water scarce regions, there is also the potential for the needs of power projects to conflict with freshwater demands (Ray, 2001).

Land-use conflicts occurring on Maori land have been resolved, at least in part, through the allocation of property rights in Hells Gate National Park and distribution of commercial benefits in the form of dividends distributed to Maoris out of revenue from geothermal power plants on sacrificed indigenous lands (Cook et al., 2019). This process has been facilitated through recognition in New Zealand law that the Maori peoples owned the resources mined from their land (Mwanza, 2018). In Olkaria, controversy has been associated with the relocation of more than 100 Maasai families by Kenya Electricity Generating Company, the state-run geothermal operator. A report by the World Bank identified adverse impacts on those affected, in part concerning the suitability of their new land for traditional spiritual practices and impacts to traditional herding practices (World Bank, 2015). Akin to the approach in New Zealand, a revenue-sharing bill was tabled and passed in the Kenyan Parliament to try and ensure adequate economic compensation for indigenous communities. This guaranteed that 2.5% of KenGen's revenue from Olkaria plants would be directed to a special fund. Of this, 75% would return to national government, with 20% and 5% directed to local governments and affected communities respectively (Mwanza, 2018).

5 Discussion

5.1 Implications of the model

The model of Malinauskaite et al. (2020) conceptualised linkages between the various ES cascade stages and processes of co-production necessary for transition from one stage to the next. Geothermal areas require the deployment of physical capital in order to actualise some ES with commercial benefits, while there are various ES human beings receive cognitively from geothermal areas. Overall, the model and geothermal examples reinforce the notion that ecosystem services are a stakeholder driven concept (Cook et a., 2020), where culturally specific and social issues will play an important role. As such, the concept relates closely to the sustainability objectives of Sustainable Development Goal 7 relating to access to energy (UN, 2015). An ES perspective can play an important role in connection with determining sustainability implications, helping to identify trade-offs between the many energy services (e.g. poverty alleviation, electricity, heating and hot water provision, cooking etc.) sourced from the development of geothermal areas and their environmental and sociocultural effects (Fell, 2017; Kalt et al., 2019). In so doing, and through valuation of geothermal ES and their impacts, a more comprehensive understanding can be gleaned of the societal wellbeing implications of transformations towards energy sustainability (Jonsson et al., 2011).

The ES examples in this paper highlighted several important issues that would require further scrutiny in a location-specific analysis. These include an evaluation of what the demands of various societal groups are with respect to geothermal resources, and how they should be valued. More information would be needed on how individuals and societal groups 'benefit' from geothermal resources. What are the actual contributions to human wellbeing and what form do they take? Especially in developing countries, these will probably be closely related to the satisfaction of various human needs (Max-Neef & Hopenhayn, 1991). Often, in an energy context, such benefits have been considered purely in relation to the alleviation of energy poverty or fulfilment of energy security (Kalt et al., 2019). However, the ES perspective, at least in a geothermal context, broadens this view to encompass a wider spectrum of benefits and impacts deriving from power projects, as well as power and equity considerations. Moreover, the characterisation of the various stages in the formation of geothermal ES and how benefits are received by human beings reveals subtle differences in how human beings demand the benefits. With respect to ES requiring physical capital inputs in order to be mobilised and appropriated, human demand relates to the receipt of the 'good' – be it a provisioning service or recreation – at a specific time and place. In the case of provisioned services, such as extracted minerals or rare metals, the receipt of the good by human beings or commercial entities will likely occur non-locally to the geothermal area. All cultural geothermal ES, unless relating to non-use value, will involve direct interactions with the area, irrespective of whether physical capital is required to mobilise and appropriate recreational benefits of commercial value or human beings receive purely cognitive benefits. The distinction between how benefits are received and the capital necessary for their realisation has important consequences for how benefits are valued. All ES benefits could be valued using techniques common to sociocultural valuation, however, the model of Malinauskaite et al. (2020) leads to a certain degree of clarity concerning those likely to belong to the monetary value domain i.e. geothermal ES with an observable exchange value in markets.

More practical implications of the analysis concern considerations of how to mitigate the ecosystem disservices of power projects or other economic developments in geothermal areas, specifically with regards to the multiple values pertaining to geothermal areas. In the case of the impacts, these need to be considered with respect to the various phases of development, from exploration (mobilisation and appropriation) to production (commercialisation) to decommissioning (post-commercialisation). A distinction exists between the adoption of open and closed loop systems with respect to hydrogen sulphide emissions of detriment to local air quality. Using closed-loop systems, gases released from geothermal boreholes are not released to the atmosphere and are reinjected into the ground (Kagel, 2007). Alternatively, emissions can be removed via chemical oxidative scrubbing or sometimes dissolved in water and reinjected into the bedrock, as has been successfully applied with hydrogen sulphide in the SulFix Project in Iceland (Karlsdottir et al., 2020; Kristjánsdóttir, 2014). When toxic pollutants are contained within geothermal brines and wastewaters, such as mercury, arsenic and boron, must be disposed of carefully at hazardous waste sites in order to prevent harm to human health (Axelsson, 2012; Kagel, 2007; Kristmannsdóttir & Ármansson, 2003). The visual and noise impacts of geothermal power plants can be mitigated in part through the sensitive siting of power plant infrastructure away from human habitations. Other mitigation measures can include the use of silencers (Bosnjakovic et al., 2019) and locating pipes and transmission lines underground, where this is feasible (Cook et al., 2017; Shortall et al., 2015), and multifarious engineering and management practices to reduce the contaminative potential of wastewaters (Hunt, 2000).

5.2 Valuation of trade-offs and impacts

In terms of the practical, contribution of the paper to aiding policy and decision-making, three key issues concerning the valuation of ES are reinforced through its analysis, all of which can be generalised to some extent to other energy-generating technologies involving land-use changes (Cook et al., 2019). These are:

1) Consideration of the decision-making context – the purpose of the valuation exercise needs to be evaluated, as the value-domain for specific ecosystem services may depend on this;
2) Understanding of stakeholder diversity – the formation of values is dependent on the type and range of stakeholders affected in the decision-making context and these need to be understood in order to comprehend land-use trade-offs;
3) Recognition of bundles – impacts to cultural ES often occur in groups e.g. aesthetics, inspiration, education and recreation.

In particular, this paper's examples have highlighted cases whereby individuals might hold multiple and conflicting values concerning a geothermal area, which will likely lead to differing societal opinions about how such resources should best be used. As Cook et al. (2019) discussed, one individual may wish to enjoy recreational experiences in undeveloped geothermal areas. However, business leaders may be motivated by the profit-making opportunities that electricity generation will provide. Meanwhile, indigenous peoples such as the Maori or Maasai, may have no economic motive, instead viewing geothermal phenomena as fundamental to their way of life. Thus, complicated and seemingly irreconcilable trade-offs may emerge between economic and sociocultural values, which can necessitate the use of advanced decision-support tools to integrate these and inform decision-makers.

Integrated valuation is value pluralist, aspiring to combine multiple and conflicting types of value in order to inform decision-making processes (Martín-López et al., 2014; Jacobs et al., 2016, Jacobs et al., 2018). This contrasts with 'hybrid valuation' (Cook et al., 2019). Hybrid valuation is unable to fully assess the trade-offs and values associated with land-use changes, or can do so only to a limited extent, and might lead to the somewhat controversial approach exemplified in this paper whereby economic compensation is given to indigenous peoples for impacts to spiritual enrichment (Cook et al., 2019). Integrated valuation techniques are an extension of hybrid forms of valuation with respect to their inclusion of complicated underlying information aspects and multiple values held by a wide spectrum of stakeholders (Baral et al., 2016). In particular, they contain four core aspects of integration: (1) knowledge systems, (2) quantitative and qualitative information, (3) values emerging across different societal domains, and (4) value articulating institutions (Martín-López et al., 2014). By necessity, carrying out integrated valuation requires the input of multiple disciplines from the natural and social sciences. Examples of integrated valuation are currently few and far between in the literature concerning geothermal areas and power projects, but there are a few cases of Multi-Criteria Decision Analysis in this context (Cook et al., 2019).

5.3 Limitations of the model and its application

The ES cascade model of Malinauskaite et al. (2020) presented a useful tool for analysing the various stages in the formation of ES specific to geothermal areas, and the various co-production processes integral to their realisation. However, the ES concept and the cascade approach are not without critics. La Notte et al. (2017) contended that any evaluation involving the ES concept is undermined by the tendency for practitioners to be inconsistent in their use of terminology. Norgaard (2010) voiced that the ES conceptualisation leads to a simplification of socio-ecological interactions and linkages to human wellbeing. The ES cascade model has also been criticised for its general omission of deeper social issues, such as power relations, socio-economic complexities, and factors of access and use (Berbés-Blásquez et al., 2016; Pascual et al., 2017). Additionally, co-production processes in the Malinauskaite et al. (2020) model perhaps overemphasise the importance of exchange value as a means of valuing human well-being benefits. As this paper has discussed, careful attention should be paid to the value domains specific to geothermal areas. In addition, the discussion concerning ES impacts of power production omits certain sub-surface effects to human well-being that may manifest as a consequence of production. These include induced seismicity during reinjection (Cook et al., 2017).

This paper applied the cascade model almost entirely with respect to the ES of high enthalpy geothermal areas and the trade-offs pertaining to their development. These have tended to receive the greatest focus to date in the academic and grey literature due to the potential scale of the impacts of mobilising geothermal resources for electricity production. As far as the authors are aware, no academic studies have yet sought to analyse the ES specific to low enthalpy fields nor the various trade-offs pertaining to the various stages of their development. ES impacts are likely to occur on a much smaller scale when low or very low rather than high enthalpy resources are appropriated, mobilised and commercialised, not least due to the absence of capital-intensive drilling and power plant infrastructure. Nevertheless, technologies such as geothermal heating, ventilation and air conditioning (HVAC) involve the drilling of shallow boreholes and installation of coils and heat exchangers. Although earth loops are buried, either vertically or horizontally, and thus do not present a visual or noise impact during operation, their installation will involve short-term, local land-use disturbances.

6 Conclusion

Co-production of ES involves overlap between the biosphere and anthroposphere, leading to the generation of meaning, value and benefits in relation to ecosystems. The case of ES from geothermal ecosystems illustrates how physical capital can be utilised to enhance human wellbeing, while cognitive associations play a central role in the formation of multiple cultural benefits. Following the development of a comprehensive CICES classification for geothermal ES, a cascade model was developed to delineate the various stages in the supply and demand of ES in geothermal areas.

The paper had the following core outcomes:

- Linkages between the respective stages in the model were identified through four co-production processes: value attribution, ES mobilisation, value appropriation, and ES commercialisation.
- A variety of ES are provided by geothermal areas, including multiple cultural associations of importance to human wellbeing. These may be realised through co-production processes, especially in the cases of provisioned minerals and heat and recreational experiences of commercial value, or which occur cognitively in the minds of beneficiaries, either directly, indirectly or through non-use value.
- Geothermal power projects can constitute a large-scale intervention from the anthroposphere into the biosphere, with the potential to cause multiple impacts to human wellbeing. These impacts needs to be carefully evaluated in the light of the specific value domains pertaining to those affected.

Future research in the area of geothermal ES could focus on many related topics. These include the issues of ethics, equity and power relations in terms of how geothermal areas and their ES are used. Who are the winners and losers from co-production processes? In addition, there are currently only a very few valuation studies in the ES literature concerning geothermal areas, leaving considerable scope for a broadening and deepening of knowledge in this regard. Furthermore, more research is needed concerning the ES of low and very low enthalpy geothermal resources and the trade-offs of their development.

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