Taming the Elements—The Use of Geothermal Energy in Iceland

Örn D. Jónsson, Bjarni F. Karlsson and Rögnvaldur J. Saemundsson

Abstract Harnessing geothermal water was an unlikely way to take on a pressing problem in Iceland: substitute oil and coal in the late thirties. As a reaction to the oil crisis in the 1970s, measures were taken by national authorities to substitute unsustainable energy. The transition was a success. The space heating system was and is based on a system for extracting and distributing geothermal water which had been strengthened in the early sixties and for the most part a fully publicly financed endeavour. In the turn of the century, as a part of the surge of privatisation in the neighbouring countries and the importance of competition, measures were taken to build technologically advanced large-scale geothermal power plants which turned to be a showcase of advanced technical knowledge but a financial disaster. In recent decades the diverging understanding of geothermal water as an energy source versus the embeddedness of the varied use of geothermal water is becoming ever more apparent and a pressing policy issue. Focus on sustainability, new technological solutions, such as smart micro-grids, and increased tourism are more compatible with the varied and embedded use of geothermal water as opposed to using geothermal resources to produce energy as a part of a large-scale technological system.

Keywords Iceland · Local embeddedness · Industrial production Technological paradigms

Ö. D. Jónsson (✉) · B. F. Karlsson
School of Business, University of Iceland, Saemundargata 2, 101 Reykjavik, Iceland
e-mail: odj@hi.is

R. J. Saemundsson
Faculty of Industrial Engineering, Mechanical Engineering and Computer Science, University of Iceland, Saemundargata 2, 101 Reykjavik, Iceland

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1 Introduction

The wide-ranging and varied use of geothermal energy is a vital part of everyday life in modern Iceland. Despite being used for washing and bathing since the country's settlement in the 9th century, geothermal water was not used for industrial purposes or space heating until the end of the 19th century and the beginning of the 20th century. Distributed heating systems were introduced in the 1930s and were slowly expanding until the 1970s, but as a reaction to the oil crisis in the 1970s measures were taken to substitute fossil fuels with geothermal energy mainly by strengthening the already existing heat distribution system. The transition was swift and successful. In fifteen years, from 1970 to 1985, the use of oil for space heating went from 50 to 5% (National Energy Authority 2016).

Beginning in the 1970s, geothermal energy was being converted to electricity as a part of the process of harnessing overheated geothermal steam for heating. At the turn of the century advanced large-scale geothermal power plants were being built as components in a country wide system of electricity generation and distribution mainly serving heavy industry, such as aluminium smelting. In 2011 40% of geothermal energy use in Iceland was for space heating and 45% for electricity. The remaining 15% were used for industrial use of heat (e.g. fish farming and greenhouses), swimming pools, and snow melting (National Energy Authority 2018b).

In recent years the use of geothermal energy for the production of electricity on a large scale has become controversial. Originally perceived as a by-product in distributed heating systems based on high temperature wells it became perceived as a new primary energy source that could sustain the effort to expand electricity production for large scale industrial production once the major sources of hydraulic power were depleted. In the process, public utilities—who had built unique technical competences in harnessing geothermal energy for space heating and electricity production—were redefined as profit-optimizing firms to take advantage of new business opportunities both in Iceland and abroad. The economic meltdown in 2008 disrupted the process and revealed the enormous financial risks involved. Furthermore, the privatization of public utilities was increasingly being questioned as well as the sustainability of the large-scale utilization of geothermal energy.

In this chapter the aim is to describe the development of the wide ranging and varied use of geothermal energy in Iceland and the controversies about its future development. Using the social construction of technology (Bijker et al. 2012) as our point of departure we describe how the utilization of geothermal energy has been guided by two different and conflicting paradigms. Originally, the construction of geothermal system was a local public undertaking out of necessity. The systems were based on direct use of low temperature geothermal water for hygiene, space heating, and greenhouses. As these systems expanded the depth and the temperature of the geothermal wells increased which provided opportunities for electricity generation as a by-product of producing geothermal water for heating and other purposes. Subsequently, a new paradigm emerged for the utilization of geothermal energy. Instead of local systems focused on diverse means of local use of geothermal water for civilian and industrial heating purposes the systems were seen as providers of generic energy to a national electrical super-grid. While the bulk of the energy was provided to large-scale industrial production the existence of an extensive national grid was expected to reduce the risk of power failures and provide cost effective electricity to regions where harnessing geothermal resources had not been seen as technically or economically feasible. Critical views of the sustainability of large-scale geothermal electricity production together with advances in technologies for local harnessing of low temperature geothermal energy and flexible electricity production and distribution (smart grids), suggest a re-examination of the perception of geothermal energy as a generic source of energy distributed through a national super-grid and a future where the focus is again on the wide ranging and varied use of geothermal water.

The chapter is divided into five sections: A short overview of our frame of reference followed by two sections tracing the history of geothermal production guided by the two paradigms of local use of geothermal fluids for various purposes and its inherent qualities (quest for comfort), and a national distribution of electricity (quest for energy). Finally, we discuss the controversies about the future development of geothermal energy and offer our conclusions.

2 Theoretical Frame of Reference

In this chapter our point of departure is the social shaping of technology and the "seamless web" of society and technology (Bijker et al. 2012). Thus, while viewing the harnessing of geothermal energy as a technical problem that needs to be solved we acknowledge that the evolution of technology is not only driven by its own rationality, but rather by a range of social, political, and institutional factors which interact in a systemic fashion.

The systemic fashion in which social, political, and institutional factors interact to shape the evolution of technology can be conceptualized as a technological paradigm and the resulting outcome as a technological trajectory (Dosi 1982). Technological paradigms are forward looking in the sense that they define what technical problems are important and what knowledge and skills will lead to solutions that are both technically viable and economically feasible. In doing so, technological paradigms are seen to shape the organization of firms and industries leading to path dependent technological trajectories which are difficult to disrupt (Arthur 1989; David 1985; Geels 2002).

An important part of a technological paradigm is the relative role and importance of different stakeholders in determining the criteria for evaluating the performance of the technology. Of particular importance is the role of users in innovation. Another important part of a technological paradigm is the relative importance of practical knowledge and scientific knowledge (Arrow 1962; Polanyi 1966; Rogers 2003; von Hippel 1988).

Technologies, such as equipment methods needed to harness geothermal energy, do not evolve in isolation because their utility and economic feasibility is usually dependent on the development of other technologies. Firms and industries specialize in the development or use of certain technology and their products and services are prerequisites for the operations of other firms and industries. The evolution of technologies is therefore constituted of mutual adjustments across technologies that affects both technological paradigms and the organization of firms and industries (Rosenberg 1982).

When a new technology emerges, technology paradigms are likely to change. New challenges and stakeholders are likely to emerge or existing challenges are addressed in a different way by different stakeholders. The challenges may be local to a geographical area or industries, and in some cases they are general. New stakeholders may bring similar and complementary perspectives already held by existing stakeholders or they may bring with them contrasting and conflicting perspectives. Conflicting paradigm may compete and if a new paradigm supersedes an existing one it resembles Schumpeter's (1942) process of creative destruction. However, conflicting paradigm may also coexist for an extended period of time.

3 The Quest for Comfort

In this section we first present a brief overview of the utilisation of geothermal energy in Iceland in the last century, before examining in more detail how this natural resource is used to enrich everyday life in Iceland and improve living.

In the beginning of the 20th century, imported coal was the primary source of household heating. It was first during the prolonged crisis of the 1930s that systematic search for an alternative energy resources became a political priority. Hydropower had become a possibility but required considerable initial investments in power plants and distribution networks. Peat had been used from earlier times in rural areas and was for a while an option in towns instead of oil and coal, as peat fitted into the existing distribution system. Peat is however a notoriously inefficient energy source and making use of geothermal heat was an attractive alternative as some farmers had achieved to use natural hot-water supplies for house heating in close proximity to hot springs. The main problem was the building of a distribution system required to deliver the hot water to the urban centres around Iceland. It required a technologically novel and robust distribution system for which there was neither available on hand engineering expertise, practical knowledge nor sufficient economic means.

Due to the high prices of imported coal and oil and despite the challenges associated with the building of a distribution system, the Reykjavík city authorities decided to heat the whole city with geothermal hot water. In 1930 the Reykjavík Heating Utility was founded and by late 1930s a distribution system was operational in a section of the capital Reykjavík, exploiting resources situated a few kilometres east of the city. The early 1940s proved to be a phase of rapid economic growth, securing further investments in infrastructure.

Due to both the damaging effects of corrosion and the technical complexity involved, as well as limited financial resources at the time, a project solving the harnessing and distribution of geothermal water was prioritized by the Reykjavík authorities. An important part of providing sufficient geothermal energy for the city was dependent on the instalment of pumps in the boreholes. Available pumps at the time were however not designed to withstand temperatures of up to 150 °C. With help from European and American engineers these and other problems were solved through continuous on-site trials and sufficient hot water could be provided to serve households and industries in the greater Reykjavík area. Using geothermal heat as a substantive or widespread solution must be seen as a clear case of a 'technological momentum' where the capabilities are eventually realized by sufficient capital, innovative use of materials such as Teflon and urethane, and an appropriate organizational system. Based on these innovations a comprehensive system was created that was sufficiently reliabile and economical. The expensive part, the drills, were provided by the state while the construction, which to a large extent was labour intensive, was provided regional municipalities.

Today, Iceland is one of the most affluent countries in the world, a welfare state fashioned after the Nordic mould. In an interesting way, the utilization of geothermal water played a part in this as it became means to overcome harsh weather conditions and dependence on animal-based food. Although affluence and wellbeing were the objective it is possible to distinguish between two different paths achieving this, one Spartan the other hedonistic. The primary objective of the Farmers movement, which had a considerable say in the developing the policy, was to avoid what their representatives regarded as the corrupting and enslaving aspects of urbanization. Cleanliness took on a metaphorical meaning as well as a practical one. The aim was a good and clean disciplined world, which coincided with the libertarian value of a balanced egalitarian society. Foreigners and Icelanders educated abroad, which represent the hedonistic path, were looking for ways to cope with the overall harsh conditions in Iceland. For this group, the use of geothermal water was not only seen as merely functional. Using greenhouses to grow grapes (along with roses) and to enrich daily life could be understood as a protest by emerging urbanites. Flowers and fruits were signs of sophistication, a cultured attempt to survive under circumstances nearly unbearable for those who were at home with a better life abroad.

In a deliberately simplified manner it can be maintained that the utilization of geothermal resources has played a significant role in the quest for comfort exemplified by the success in space heating, food production and outdoor activities (Jónsson and Rastrick 2017). The quest for comfort is a universal goal and attaining greater control over the environmental settings; summer all year long. Due to the short summer growing root vegetables has been difficult while growing vegetables such as tomatoes, capsicum and cucumbers has been a part of the stable for decades. Iceland's rapidly increasing capabilities and skills in utilizing geothermal water in a creative way, e.g. running a restaurant in a greenhouse where the locally produced food is consumed, go hand-in-hand with the global trend in production and consumption of food and the growth of tourism where the number of visitors grew from less than 200,000 in 1995 to over 2,000,000 in 2017.

One of the most surprising aspects of the utilization of the geothermal is the popularity of outdoor swimming pool where the Jacuzzi-like outdoor hot tubs have become one of the most frequented gathering places in the country, comparable to the Parisian café, the English pub, the Mediterranean church plaza, the ancient Turkish Hamman, and, closer to home, the Finnish sauna. The tubs are visited daily by young and old and social status is insignificant all year round (Jónsson 2009). Furthermore, the Blue Lagoon—and similar geothermal spas—are some of the most popular tourist attractions in the country. Outdoor bathing can in a sense be seen as a convergence of the Spartan and the hedonistic value sets; geothermal living, which has become a cultural identity valued by the local inhabitants and their foreign visitors.

Once systems for distributing geothermal water were in place and technical capabilities were developed to harness geothermal resources of higher temperature than before, further plans for the utilization of the country's geothermal resources were considered. This time the utilization was not driven by the quest for comfort, but rather by the quest for energy to power large-scale industrial processes.

4 The Quest for Energy

"It doesn't matter how much we build, the demand will always exceed the supply" said Hördur Arnarson, the CEO of the National Power Company (Landsvirkjun) at the company's annual general meeting in April 2016. These words reflect the belief that the demand for energy will continue to rise and that the company will always be able to find buyers for all the electricity that can be produced in Iceland.

This optimism is not new in Iceland. It drove ambitious entrepreneurs in the beginning of the 20th century when they planned to harness the energy in the country's waterfalls and was the basic premise of public policy in the 1960s which lead to the establishment of the National Power Company for the large-scale production of electricity for industrial processes using hydropower. In the beginning of the 21st century it was the guiding principles for the large-scale utilization of geothermal energy for electricity production.

The production of electricity using geothermal energy started primarily as by-product of generating geothermal water for heating. As local low temperature wells (temperature less than 100 °C) became fully utilized, public utilities looked for opportunities to harness sources of higher temperature containing overheated steam. Electricity is generated as the steam is cooled and then the resulting geothermal water can be distributed and used for space heating and other purposes.

The higher temperatures created new technical problems that were solved gradually in the period from the late 1960s and into the 2000s. These problems related to prospecting and the drilling of the wells and the chemical composition of the overheated geothermal fluid. In both cases there were large regional variation which made it difficult to transfer practical knowledge from one site to another and lead to increased dependence on scientific knowledge and the use of advanced engineering methods and materials.

At the turn of the century two public utility companies specializing in the extraction and distribution of geothermal water—Suðurnes Heating Utility (Hitaveita Suðurnesja) and Reykjavik Heating Utility (Hitaveita Reykjavíkur)—were successfully operating geothermal power plants producing both electricity and geothermal water. These power plants, which became online in 1978 and 1990, were improved and expanded until 2007 and 2005, respectively.

In the early 2000s there was a change in the organization and strategy of regional utility companies. Companies originally providing separate utilities, such as water, heating, and electricity, were merged into single entities and in some cases into publicly owned limited liability companies. Furthermore, changes were made to legislation related to electricity production and distribution opening up the state monopoly and creating opportunities for the regional utility companies to produce and distribute electricity beyond their own regional systems. Especially, this created opportunities for the regional utilities to provide energy to large scale industrial buyers. Subsequently, Reykjavik Heating Utility (now as the merged utility Reykjavik Energy) and Sudurnes Heating Utility built new geothermal power plants that are primarily intended for producing electricity for large-scale industrial producers and both started operation in 2006. In the period 2000–2017 the production of electricity by geothermal power plants increased from 1.300 to 5.200 Gwh,

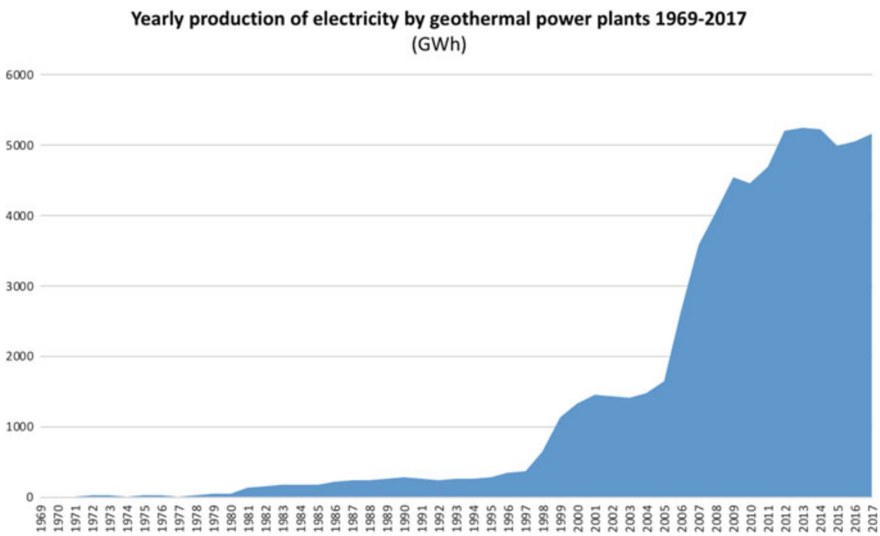

Fig. 1 Yearly production of electricity by geothermal power plants in Iceland 1969–2017. *Data Source* National Energy Authority (2018a)

which is a fourfold increase (see Fig. 1). In 2016 the total electricity production in Iceland was 18.500 Gwh where about 80% of the energy was used by large-scale industrial processes (mostly aluminium smelting), 15% was used by small and medium sized firms (SME), and 5% by households (National Energy Authority 2017).

The use of geothermal power plants for producing electricity on a large-scale not only increased the supply of electricity but it also changed the nature of the utilization of geothermal energy from the perspective of the relationship between primary energy and energy consumption. While 81% of the primary geothermal energy was harnessed through high temperature wells (mostly to produce electricity) less than half of it was consumed (National Energy Authority 2010). The reason is the low efficiency of the conversion from geothermal energy to electrical energy and the lack of demand for the excess hot water being created in the process.

The financial crisis of 2008 slowed down the expansion of the large-scale production of electricity using geothermal energy. Lack of access to capital reduced the rate of investment, but the crisis also exposed the financial risks taken by the utility companies because of the increase in the value of foreign debt. For example, Reykjavik Energy 2011 had to devise extreme measures ("The plan") in order to save the company from becoming bankrupt (Fig. 2). The price of hot water for household use was raised and special efforts were made to lower the debts. Furthermore, the crisis brought with it a change in mood and a more critical view about the profitability and sustainability of large-scale production of electricity using geothermal energy (Shortall et al. 2015; Shortall and Kharrazi 2017).

Even if the development of large-scale production of electricity using geothermal energy has slowed down the scientific and engineering competencies are still being developed and deployed. The National Power Company is building a new power plant, and planning another one, to provide electricity for large-scale industrial production in the northern part of the country. Several engineering firms

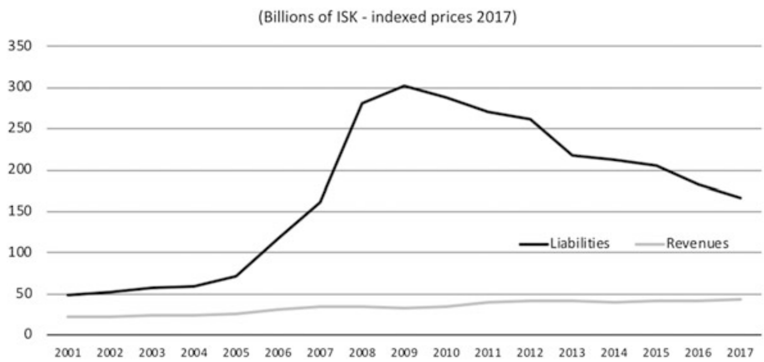

Fig. 2 The effects of the financial crisis in 2008 on the financials of Reykjavik Energy (Orkuveita Reykjavikur). *Data Source* Reykjavik Energy annual reports 2002–2018 (https://www.or.is/english/finance/financial-reports)

are designing and operating geothermal systems abroad, with recent projects in Ethiopia (Reykjavik Geothermal) and China (Arctic Green Energy). Furthermore, an international research project is prospecting and drilling geothermal wells at even higher temperature and length (Iceland Deep Drilling Project). However, most of the regional utilities, such as Reykjavik Energy, have returned to their core business of serving their local constituencies.

5 Future Development of Geothermal Energy

In the previous sections we have described how the use of geothermal energy in Iceland has been guided by two paradigms which we have labelled the quest for comfort and the quest for energy. In the former case the construction of systems for the distribution of hot water was a local public undertaking which was not a matter choice but out of necessity. The systems were based on direct use of geothermal water for hygiene, space heating, greenhouses, and drying—use which mainly improved comfort and the quality of life for citizens. In the latter case–initially driven by relatively large public utilities but later by the National Power Company and private engineering firms—systems were constructed to produce electricity for large-scale industrial use. While the primary motive was to monetize the country's natural energy resources it was also argued that large scale industrial use of electricity would justify the investment in an extensive national grid for electricity distribution. The existence of the grid would reduce the risk of power failures and provide cost effective electricity to regions where harnessing geothermal resources had not been seen as technically or economically feasible, thus increasing the comfort and quality of life in those regions.

What has been common to the two paradigms is gradual building of capabilities through learning and the creation of organizational systems. Early attempts in Iceland to harness geothermal energy for direct use of heat were governed by a pressing need, rather than a previously established technical or economic feasibility. Attempts at constructing a distribution system for space heating met with numerous challenges related to corrosion, pressure, and the loss of heat. Furthermore, the challenges were different for each geothermal area and the sources of these differences were not well understood. Thus, building each of these local distribution systems was a major practical as well as engineering accomplishment that was based on relatively low-cost experimentation and to a large degree on the accumulation of tacit knowledge that was difficult to transfer across sites. In comparison the learning related to the building of geothermal power plants for producing electricity was more codified and developed in the context of a large technical system. By converting the geothermal energy into electricity previous challenges of distributing geothermal fluids can be avoided. By subscribing to universal standards of electricity distribution an existing electricity grid can be used for distribution without any context specific learning. Geothermal energy simply becomes a commodity within a large technical system that operates independently of the energy sources being used. However, specific challenges still remained related to drilling and the handling of the geothermal fluid. In order to gain access to the vast amount of primary energy needed—due to low efficiency of conversion—deeper wells were needed that operated at higher temperatures and pressure. This environment is more difficult to control and direct experimentation is much more expensive with a higher risk of failure. Thus, the development of technical capabilities has become more science-based making extensive use of complex simulation models in order to reduce the uncertainty associated with direct experimentation without being able to eliminate the related risks. This has eventually turned into an "iron cage" where the actual purpose of producing a profitable product for large scale industry have been driven by instrumental rationality.

The main difference between the two paradigms concerns the generality of the energy source which affects the locality and scale of its utilization and concerns about sustainability. In the quest for comfort the emphasis was on the specificity of the energy source and how its characteristics can be used for multiple purposes. In the quest for energy the emphasis was on the generic aspects of geothermal energy and the how it could be converted into a universal energy source. In the former case the utilization was local on a limited scale, while in the latter case larger scale exploitation became economically feasible through access to a national—and even international—distribution networks. The larger scale, however, created concerns about the degree to which a geothermal resource is renewable and the limits of natural recharge given high rates of utilization.

The concerns about sustainable utilization of geothermal resources added to previous concerns and controversies about the extensive utilization of hydropower and the protection of the inhabitable Icelandic highlands. On one hand, the market and the state have since the 1960s sought to exploit the energy resources residing in the highlands, and on the other hand, parts of the civil society have resisted the exploitation by stressing the future value of conserving the unique nature of the highlands. The tensions between exploitation and conservation have influenced policy making and NGOs have played an important role in creating public awareness of environmental issues.

The first environmental laws in Iceland were established in 1956. An advisory committee was created, *The Nature Conservation Council*, and local committees for nature conservation were set up in every administrative district. The minister responsible was the minister of Education. Around 1990 there were large changes in environmental legislation in Iceland. The Ministry for the Environment was created and new laws were established requiring the evaluation of environmental impact of all construction projects. The application of the new laws was in focus in the largest hydroelectric dam project in the history of Iceland—the Kárahnjúkar dam—which in 2002 the National Power Company committed to build to service an Alcoa aluminium smelter in the eastern part of the country. The decision was very controversial and the opposition to the project mobilized a large number of NGOs, but at the same time the Nature Conversation Council was abolished and its office closed down.

The leading NGO for nature conservation and environmental protection is *The Icelandic Environmental Association* which was founded in 1969. Today, the association has over 40 member-societies all over the country with over 5000 individual registered members. Its role is to protect Icelandic nature and be an active participant in strategic planning, education, and informed decision-making in matters that relate to land use, natural resources and the environment. Recently, the association has played a key role in synchronizing the opposition of multiple NGOs. For example, *Iceland National Park* is a campaign advocating for the protection of the Icelandic highlands. The campaign has resulted in a coalition of 28 organizations and is still growing; environmental NGOs, outdoor recreational clubs and the Icelandic Travel Industry Association. The coalition wants to see the highlands turned into a national park. This campaign started as an aftermath to a concert organised in 2014 by a nature conservation association.

To reconcile the competing interests of nature conservation and energy utilization the Icelandic government has created a process called the Master Plan for Nature Protection and Energy Utilization (Master Plan 2018). While the idea had been around since the 1980s the work did not begin in earnest until 1999. The dual purpose of the process is to create a stable consensus about what areas should be protected and what areas are available for exploitation. The process is built around the classification of all options for energy utilizations, including geothermal options, into one of three classes: *permitted—possibly permitted—not permitted*. Expert committees evaluate the impact of each option and a steering committee integrates the results from the expert committees and classifies the option. The process is transparent allowing for inputs from all stakeholders. The process started its fourth phase in 2017 and is expected to finish in 2021.

Differently from other countries the current energy debate in Iceland has not been concerned with finding alternatives to fossil fuels. Instead it has focused on the future value of conserving the unique nature of the highlands, which, for many, has become an important part of the country's identity and valuable in itself (Cook et al. 2018). However, with an increased awareness of the need to improve the sustainability of the world's energy systems alternative modes of energy production along with the increasing sophistication of techniques used to monitor and control both production and use have come into the fore. By optimizing the inherent qualities of the different energy sources, such as solar cells and wind turbines, generation with a real-time coordination using a smartgrid, these grids a can function autonomously (as separate islands) or connect to a larger grid. These technological developments have co-evolved with the increasing role of the prosumer (Ritzer and Jurgensen 2010), i.e. a consumer that takes on tasks that hitherto had been an integrated part of the production and distribution process. In the Icelandic context these developments are compatible with the original paradigm—the quest for comfort—guiding the utilization of geothermal energy in Iceland. The municipalities, as a civil society or a village, can be seen as the prosumer, i.e. involved in both the production and consumption of geothermal water for improving the comfort of the collective. However, the paradigm guiding the use of geothermal energy for producing electricity seems to be the opposite, as it is based on clear separation between producers and consumers and is less dependent on regional characteristics and differences. Furthermore, many see it as destroying the future value of a preserved nature.

In recent years we have seen an increased interest in using local solution to address the energy provision for areas in Iceland where the harnessing of geothermal energy has not been deemed economically and technically feasible. For example, the National Grid Company (Landsnet) has experimented with the use of smart micro-grids in the north-western part of the country (Vestfjord) and recently it has been reported that dependence on oil and costs can be significantly reduced in the same region using heat pump technology. Another example is in the south-eastern part (Hornafjordur) when improvement in prospecting and drilling technology have led to the discovery of geothermal sources to use for space heating that is both technically and economically feasible. These developments, along with relatively few inhabitants that are without access to geothermal water—less than 7% of the total population—have made it less convincing that the large-scale production of electricity for industrial use is the best way to secure the delivery of energy at reasonable prices to areas without access to geothermal water.

6 Conclusion

While predictions about the future tend to be wrong it is tempting to predict that recent development in Iceland signals the decline of the quest for energy paradigm and the revival of the quest for comfort. A sustainable energy system for heating and electricity is almost in place in Iceland—the few "cold" areas that are left are likely to develop local solutions in the near future. The value-creation potential of locally produced geothermal water for varied direct use—the quest for comfort for inhabitants and their visitors—is currently much higher than for nationally produced electricity. Furthermore, the environmental impact and financial risks from exploiting this potential is much lower than exploiting geothermal primary energy at a large scale. At the same time scientific knowledge and technical capabilities have been built for harnessing high temperature geothermal energy sources—capabilities that may not be in high demand domestically but hold the potential of providing alternative energy sources to reduce dependency on fossil fuels abroad. The challenge for policy makers is to understand if it is desirable and feasible to continue to emphasize the development of knowledge and capabilities for the utilization of high temperature geothermal resources, while at the same time developing local capacity to continue the quest for comfort through varied direct use of geothermal water. In the former case the taming of the elements continues, but for use outside the country. In the latter the elements have already been tamed but value is created through creativity and innovation in their local use.

References

Arrow KJ (1962) The economic implications of learning by doing. Rev Econ Stud 29(3):155–173

Arthur B (1989) Competing technologies, increasing returns, and lock-in by historical events. Econ J 99(394):116–131

Bijker WE, Hughes TP, Pinch T (eds) (2012) The social construction of technological systems. New direction in the sociology and history of technology. MIT Press, Cambridge, MA

Cook D, Davíðsdóttir B, Kristófersson DM (2018) Willingness to pay for the preservation of geothermal areas in Iceland—the contingent valuation studies of Eldvörp and Hverahlíð. Renew Energy 116:97–108

David PA (1985) Clio and the economics of QWERTY. Am Econ Rev 75(2):332–337

Dosi G (1982) Technological paradigms and technological trajectories. Res Policy 11:147–162

Geels FW (2002) Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res Policy 31:1257–1274

Jónsson ÖD (2009) Geothermal living. University of Iceland Press, Reykjavik

Jónsson ÖD, Rastrick Ó (2017) Enjoying the outdoor pool in a cold climate. Appropriate technology, utilization of geothermal resources and the socialization of everyday practices in Iceland. Geotherm Energy 5:2–14

Master Plan (2018) The master plan for nature protection and energy utilization. http://www.ramma.is. Accessed 5 Apr 2018

National Energy Authority (2010) Use of geothermal energy for the production of electricity and direct use until 2009. National Energy Authority OS-2010/02

National Energy Authority (2016) Residential heating in Iceland by energy source 1970–2010. http://www.nea.is/the-national-energy-authority/energy-data/data-repository/. Accessed 16 Mar 2016

National Energy Authority (2017) OS-2017-T015-01: electricity consumption in Iceland 2016 [data file]

National Energy Authority (2018a) OS-2018-T005-01: installed electrical capacity and electricity generation of geothermal power plants in Iceland 1969–2017 [data file]

National Energy Authority (2018b) Use of geothermal energy in Iceland. https://orkustofnun.is/orkustofnun/orkutolur/jardhitanotkun/. Accessed 22 Mar 2018

Polanyi M (1966) The tacit dimension. University of Chicago Press, Chicago

Ritzer G, Jurgensen N (2010) Production, consumption, prosumption: the nature of capitalism in the age of the digital 'prosumer'. J Consum Cult 10(1):13–36

Rogers EM (2003) Diffusion of innovations. Free Press, New York

Rosenberg N (1982) Inside the black box: technology and economics. Cambridge University Press, Cambridge

Schumpeter JA (1942) Capitalism, socialism and democracy. New York, Harper & Row

Shortall R, Kharrazi A (2017) Cultural factors of sustainable energy development: a case study of geothermal energy in Iceland and Japan. Renew Sustain Energy Rev 79:101–109

Shortall R, Davíðsdóttir B, Axelsson G (2015) A sustainability assessment framework for geothermal energy projects: development in Iceland, New Zealand and Kenya. Renew Sustain Energy Rev 50:372–407

von Hippel E (1988) The sources of innovation. Oxford University Press, New Your

Örn Daniel Jónsson is professor on innovation and entrepreneurship at the School of business at the University of Iceland and has a Ph.D. in Economic Geography from Roskilde University, Denmark. In his research he has focused on, innovation, product development, food culture and the impact of the geothermal on everyday living.

Bjarni Frimann Karlsson is an assistant professor in accounting and auditing at the School of Business at the University of Iceland and has a master degree in public administration from SDU, Denmark. In his research he has focused on financial statement analysis and investigation the processes leading to the collapse of the savings banks in Iceland.

Rögnvaldur Saemundsson is an associate professor in Industrial Engineering at the University of Iceland and has a Ph.D. in Technology Management from Chalmers University of Technology. In his research he has focused on technology-based entrepreneurship and innovation including its history in Iceland.