9 GEOTHERMAL POWER GENERATION

	2010	2013	2014	2010-2014 (% change)
New capacity additions (MW)	221	389	528	139%
Cumulative installed capacity (GW)	10.9	11.6	12.6	15.6%
Typical global total installed cost range (2014 USD/kW)	1 900 to 5 500	1 900 to 5 100	1 850 to 5 100	n.a.
Global LCOE range (2014 USD/kWh)	0.05 to 0.15	0.07 to 0.15	0.04 to 0.10	n.a.

Notes: 2014 deployment data are estimates. n.a. = data not available or not enough data to provide a robust estimate.

Highlights

- Geothermal power generation is a mature, commercially available solution to provide low-cost base load capacity in areas with excellent high-temperature resources that are close to the surface.
- Between 2007 and 2014, the LCOE of geothermal varied from as low as USD 0.04/kWh for second-stage development of a field to as high as USD 0.14/kWh for greenfield developments.
- Geothermal power plants are capital intensive, but they have very low and predictable running costs. Development costs have increased over time as engineering, procurement and construction (EPC) costs and commodity prices have risen, as well as because of the rise in drilling costs, which is in line with trends in the oil and gas sectors.
- Total installed costs appear to have stabilised, but deployment remains modest, and not enough data is available to identify if this is statistically significant.
- Projects that are planned for the period 2015 to 2020 expect to be able to reduce installed costs below recent levels.

Introduction

Geothermal resources consist of the thermal energy available from the Earth's interior, which is stored as heat in rocks, as steam or hot water (hydrothermal resources) in the Earth's crust, or in active geothermal areas on the Earth's surface. Geothermal development reached a total installed capacity of around 12 gigawatts (GW) at the end of 2013, with virtually all of this development in active geothermal areas with good resources.

Geothermal power generation is a mature, commercially available solution to provide low-cost baseload capacity in areas with excellent high-temperature resources that are close to the surface. The wider deployment of geothermal power outside areas of active geothermal activity, using the so-called "enhanced geothermal" or "hot dry rocks" approach, is much less mature and the costs are typically significantly higher, making the economics much more challenging.

High-temperature water or steam-based resources (>180°C) are the most efficient for electricity generation, as the liquid can be used directly by dropping the pressure to create steam (in the "flashing" process) that can drive a turbine. Where only medium-temperature resources are available, more expensive "binary" plants are required. These use a heat exchanger to create steam from a liquid with a low boiling point for subsequent use in a steam turbine. These plants have higher capital costs and somewhat lower efficiency, which also raises costs for a given desired output due to the higher energy input needs.

The availability of existing geothermal resource mapping can help to reduce the costs of development, as it reduces the uncertainty about where initial exploration should be conducted. At this point a programme of baseline environmental monitoring is recommended. The initial exploration (e.g. surface seismic) is then used to map the sub-surface in more detail and identify promising geothermal reservoirs suitable for electricity production. This is then followed by exploratory drilling, which will provide additional information on sub-surface conditions. The exploratory drilling helps to define the extent of the reservoir and its characteristics (e.g. pressures, temperature, flow rates, etc.). This is a time-consuming and expensive process, and presents a barrier to the uptake of geothermal power generation, as poorer than expected results may require additional drilling or indicate that wells will be needed over a larger geographic area in order to generate the desired level of electricity.

However, with this information a field development programme can then be elaborated, which involves the siting and design of the production and re-injection, reservoir management programme, infrastructure and power plant design. However, the geothermal system management programme will evolve over time as a better understanding emerges regarding the reservoir and its flows and characteristics when in production. In addition, regular "make-up" wells will need to be drilled as the productivity of individual wells declines over.[33]

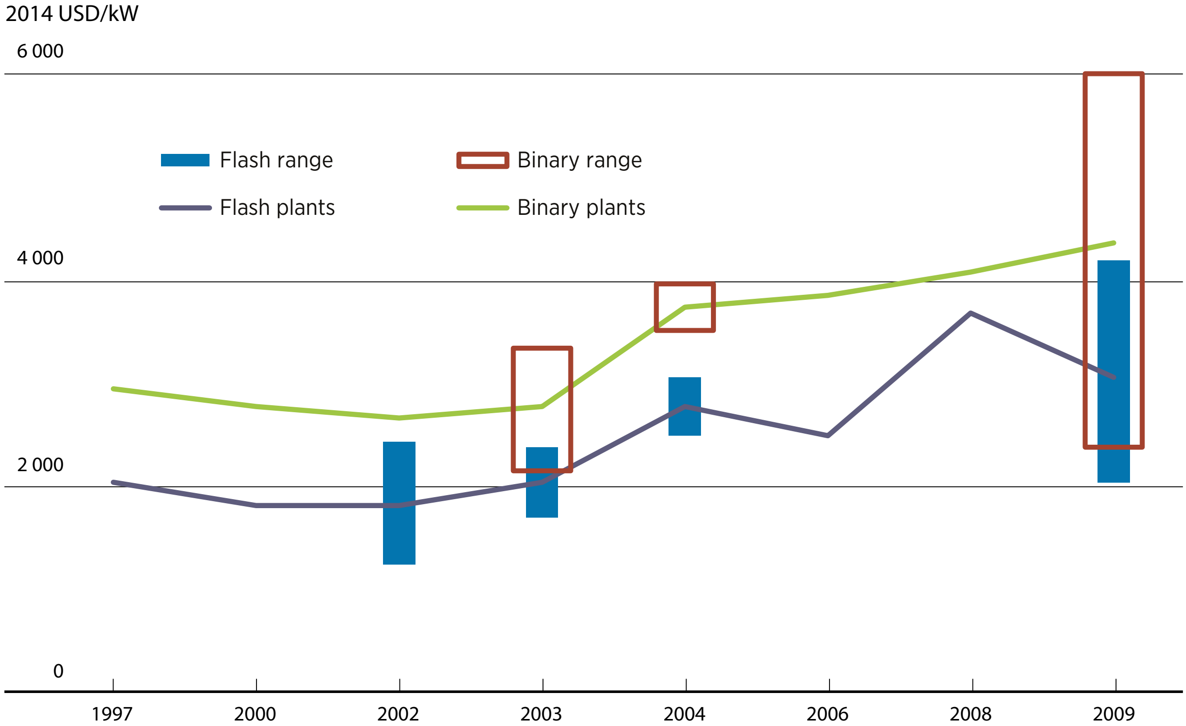
Geothermal power generation installed costs

Geothermal power plants are capital-intensive, but they have very low and predictable running costs. Development costs have increased over time as engineering, procurement and construction costs (EPC), commodity prices and drilling costs have risen (which is in line with trends in the oil and gas sectors). The total installed costs of a geothermal power plant are composed of the following:

- Exploration and resource assessment costs;
- The drilling of production and re-injection wells. This requires a contingency plan, as a success rate of 60% to 90% is the norm for production (Hance, 2005; GTP, 2008);
- Field infrastructure, the geothermal fluid collection and disposal system, and other surface installations;
- The power plant and its associated costs; and
- Project development and grid connection costs.

[33] *The alternative is to let capacity factors decline over time as the energy available from existing wells drops. This is an economic question and the trade-off will depend on the cost of additional wells, balanced against the revenue from higher output.*

Figure 9.1: Total installed costs for geothermal power stations, 1997 to 2009



Source: IPCC, 2011.

The geothermal field characteristics will have a significant influence on what type of power plant can be used (flash or binary), on well productivity and energy delivery,[34] and on the capacity for which it is economic to provide steam, given the quality of the geothermal field and its geographic distribution.

Between 2000 and 2009, total installed costs for geothermal power plants increased by 60% to 70% (IPCC, 2011). Project development costs rose with general increases in civil engineering and EPC costs over that time, and also as a result of the above average level of inflation in drilling costs experienced over this period – the result of cost inflation in the drilling business tied to rising oil and gas prices. The total installed costs of conventional condensing "flash" geothermal power generation projects grew to between USD 1 900 and USD 3 800/kW in 2009 (Figure 9.1). The more expensive binary power plants saw installed costs for typical projects increase to between USD 2 250 and USD 5 500/kW in 2009 (IPCC, 2011).

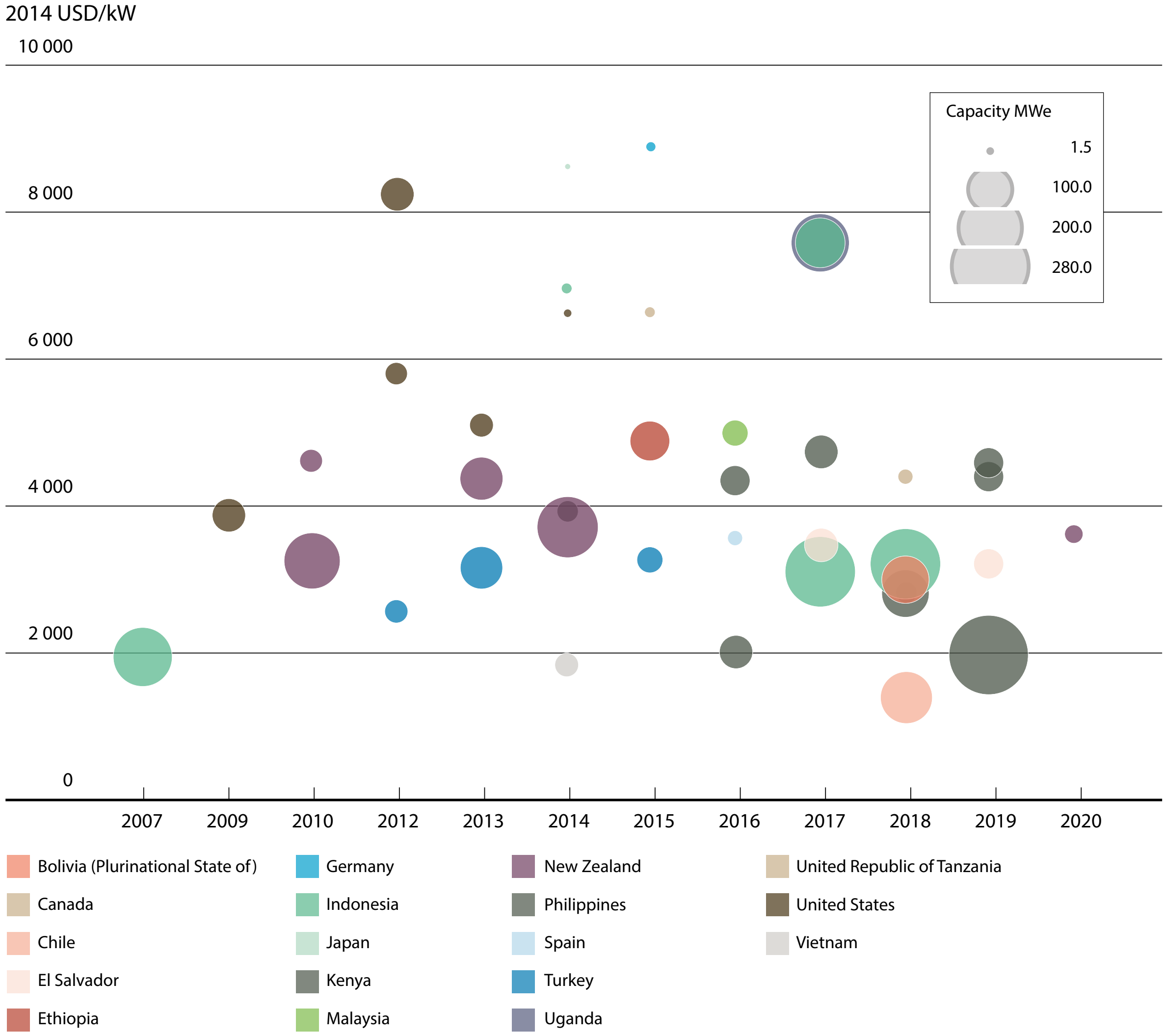
[34] The well productivity and energy delivery will affect the number of wells required for a given capacity of electricity. These factors, and the geographic spacing of these wells, will have a significant impact on overall development costs.

Project costs can be as low as USD 1 500/kW where capacity is being added to a geothermal reservoir which is already well characterised and where existing infrastructure can be utilised, but such cases are exceptional. Data for recent projects (Figure 9.2) fit within the general range band in Figure 9.1, but there are also small projects in new markets for geothermal power for which costs are higher.

However, the cost ranges in Figure 9.1 are narrow compared with some of the analysis in the literature and may represent the lower end of the cost range when exploiting the best geothermal resources. Analysis for the United States (Figure 9.3) suggests a wider range for binary plants exploiting low-temperature resources, based on the power plant costs alone (i.e. excluding production and injection wells) (NREL, 2012).

The estimates of total installed costs for the remaining geothermal resources in the United States cover a very wide range – from around USD 1 500/kW to over USD 10 000/kW (Augustine, 2011). Much of this supply curve for the United States is not economic and does not represent typical geothermal project costs, but it does show the importance of identifying the best

Figure 9.2: Installed capital costs for geothermal power projects, 2007 to 2020



Source: IRENA Renewable Cost Database and GlobalData, 2014.

geothermal reservoirs and geothermal resources for project development. Cost ranges for small-scale, low-temperature resource binary plants are therefore likely to be higher than those for excellent geothermal reservoirs and resources, and are typically in the range from USD 5 000 to USD 10 000/kW.

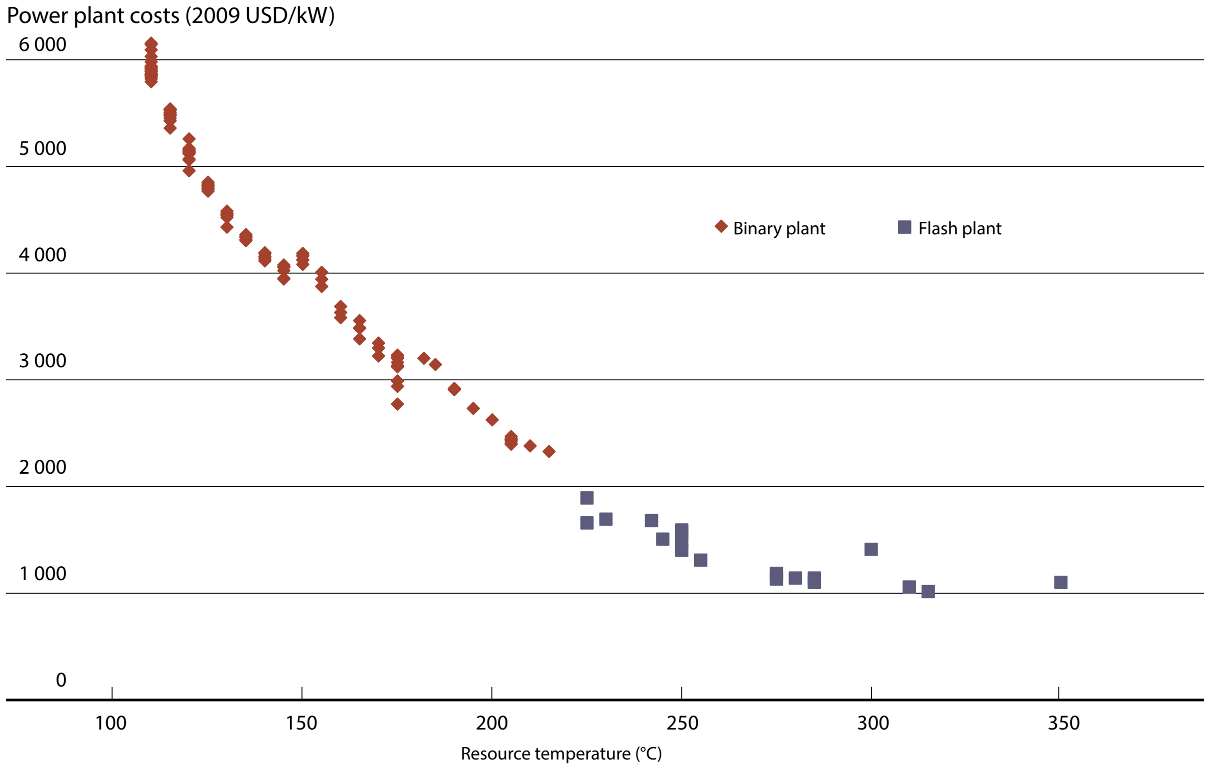
Figure 9.4 presents the estimated breakdown of capital costs for the development of two 110 MW flash geothermal power plants in Indonesia with total installed costs of around USD 3 830/kW. With total power plant costs of USD 1 560/kW, the power plant accounts for 42% of the total installed costs. Production wells, injection wells and smaller test wells together account for around one-fifth of the total cost, while the steamfield development accounts for 14%.

The levelised cost of electricity of geothermal power generation

The levelised cost of electricity (LCOE) of a geothermal plant is determined by the usual factors, such as installed costs, operations and maintenance (O&M) costs, economic lifetime and the weighted average cost of capital. However, geothermal power presents more dynamic questions than for some other renewables and projects must be carefully managed in order to optimise the resource.

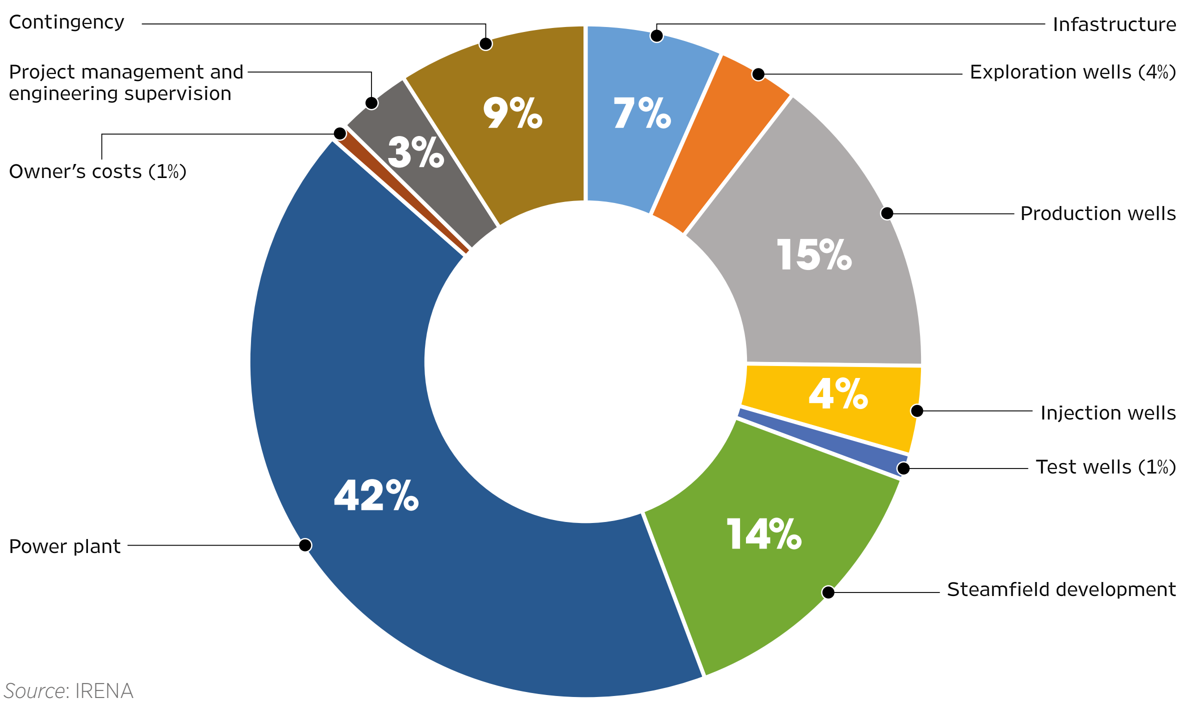
There is an ongoing requirement for expert professional and technical staff to manage a programme of reservoir monitoring, well testing and maintenance and drilling. A lack of understanding of these factors can introduce greater uncertainty into the development of

Figure 9.3: Indicative power plant only costs for geothermal projects by reservoir temperature



Source: NREL, 2012

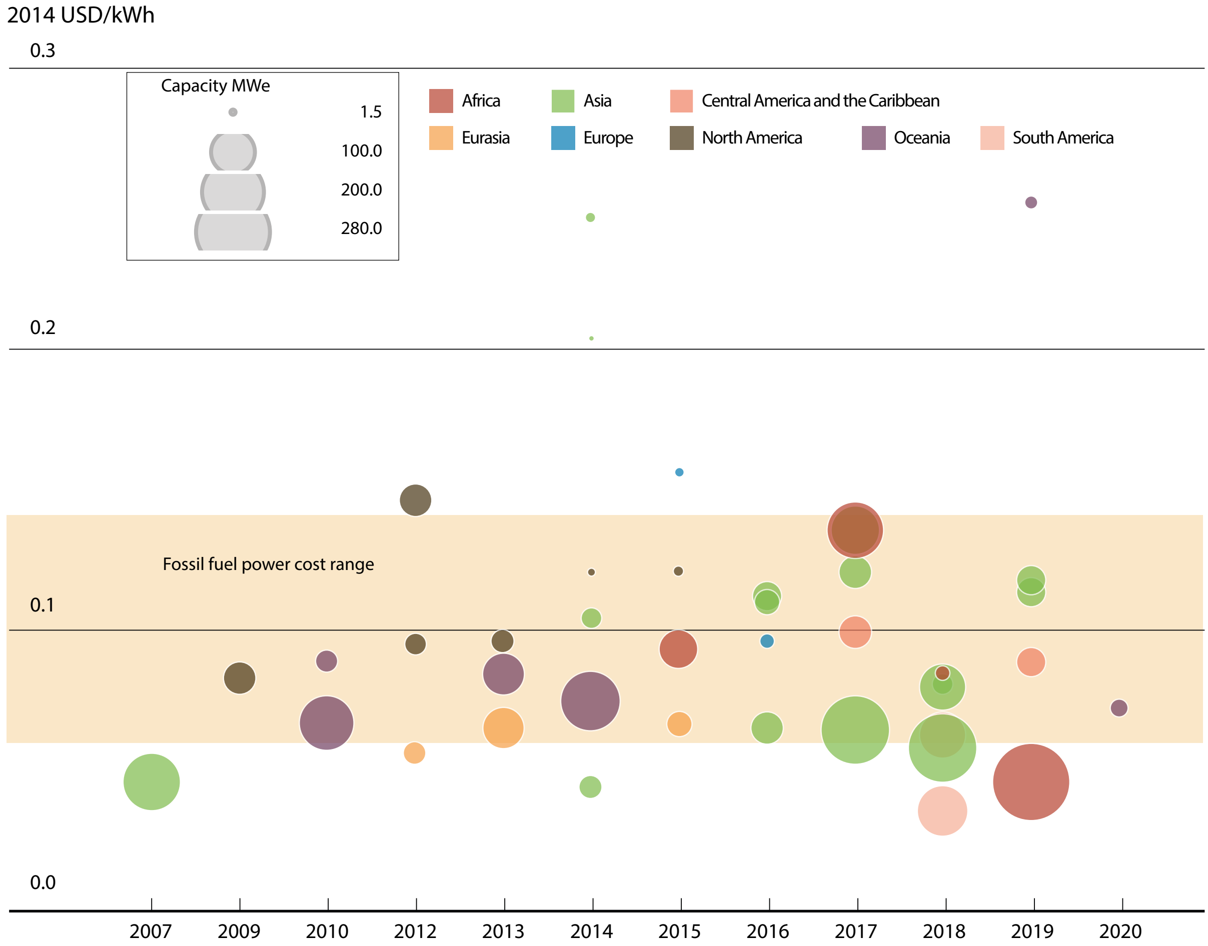
Figure 9.4: Total installed cost breakdown for two proposed 110 MW geothermal plants in Indonesia



Source: IRENA

geothermal projects and may increase financing costs, compared with technologies such as wind. However, this uncertainty is typically manageable in mature geothermal markets where financing institutions have had previous experience with the industry and where there are sufficiently experienced professional and technical experts working on the project. The LCOE calculations presented here must be considered an indicative estimate of the *ex ante* LCOE. The actual LCOE will only be known at the end of the project's

Figure 9.5: The levelised cost of electricity of geothermal power projects by region and size



Source: IRENA Renewable Cost Database and Global Data, 2014

economic life, but would be expected to differ from the values presented here.

Figure 9.5 presents the LCOE for geothermal projects assuming a 25-year economic life, O&M costs of USD 110/kW/year, [35] capacity factors based on project plans (or national averages where data are lacking), two sets of make-up and re-injection wells over the 25-year life and the capital costs outlined in Figure 9.2. Between 2007 and 2014, according to the data available, the trend in LCOE was increasing in line with trends in capital costs (Figure 9.1 and 9.2), and the LCOE varied from as low as USD 0.04/kWh (Figure 9.5) for second-stage development of a field to as high as USD 0.14/kWh for greenfield developments. Looking beyond 2014 to proposed projects between 2015 and 2020, there is an expectation that a range of large projects might see the LCOE of geothermal plants being developed start to decline. It remains to be seen whether these projects can be developed at the cost levels indicated in Figure 9.2, and if they will perform as expected to deliver the projected LCOEs in Figure 9.5.

[35] *Lower costs of USD 68 to USD 92/kW/year are reported for some countries (Sinclair Knight & Merz, 2014) but these exclude make-up and re-injection wells and it is not clear that they are indicative for average projects.*