

Guidelines for the Preparation of Geothermal Feasibility Studies

Ari Ingimundarson, Gudni Axelson, Benedikt Steingrímsson, Ingi Ingason, Olafur Arnason, Thrainn Fridriksson,
Mariano Gonzales Serrano

Grensásvegi 9 108 Reykjavík, Iceland

ariingi@gmail.com, gax@isor.is

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ABSTRACT

The paper presents guidelines for the preparation of geothermal feasibility studies. A geothermal feasibility study report is a document that collects and presents information necessary to determine the technical and financial viability and level of risk of a geothermal energy project and its compliance with environmental and social safeguards. The feasibility study report is created by the entity developing the geothermal project or the project developer. Typically, the developer is a public utility or, an independent power producer (IPP) or an investor- owned utility.

The objective of the guidelines is twofold. Firstly, it is to assist developers in the preparation of geothermal feasibility studies by giving a description of the required content. Secondly, the objective is to present to financing entities guidelines to assess if a feasibility study report is of adequate quality. The feasibility study is used by financing entities to assess the risks associated with the project. Risks and risk categories in geothermal projects are presented and the main handling approaches discussed. A content list of a typical feasibility study was created based on recommended contents for other energy projects. However, several aspects of geothermal projects set them apart from other power generation projects. In particular the risk profile differs primarily due to the presence of the geological resource risk. The content list includes items: Project concept and background; Market concept and analysis; Geothermal resource assessment; Location and site; Environment and social safeguards; Engineering and technology; Project execution plan and schedule; Financial analysis and investment appraisal. Each item of the list above is treated and the required content in a feasibility study report explained.

1. INTRODUCTION

The purpose of this document is to provide guidelines for the preparation of feasibility studies for geothermal power projects in accordance with best industry practices. A geothermal feasibility study is a document, prepared by the project developer, that collects and presents information necessary to determine the technical and financial viability of a geothermal energy project and its compliance with environmental and social safeguards. In a broad sense, a feasibility study is a living document that evolves through the project preparation. Feasibility studies may be prepared for several different purposes such as to guide internal business decisions of the projects owners or to demonstrate the economic viability of the project and its alignment with the country's energy strategy to public stakeholders. The guidelines presented here refer, specifically, to feasibility studies prepared for the purpose of securing financing¹ for the project.

The developer prepares the feasibility study so that financing entities can assess the risks associated with the project. A feasibility study report should identify the main risks and describe how they will be managed. A necessary condition for a financing entity to lend to the project is that it assesses project risks to be in line with what they are willing to accept considering all loan conditions.

The objective of these guidelines is twofold. First, to assist developers in the preparation of geothermal feasibility studies for financing entities by giving a description of the required content and structure. The second objective is to present guidelines to financing entities to assess whether a feasibility study is of adequate quality and scope.

The topics addressed in a feasibility study for any power generation project are quite similar irrespective of the energy conversion technology. However, several aspects of geothermal projects set them apart from other power generation projects. Geothermal projects are unique among power generation projects because of their risk profile, characterized by high upstream risk due to resource uncertainty and high cost of drilling. Geothermal project risks and risk handling approaches are presented in Appendix A.

Even though the focus is on geothermal projects for electricity production, most of the recommendations presented are equally valid for direct use geothermal projects.

¹ A frequently used term when discussing feasibility studies is that it is bankable. This refers to the ability of the feasibility study to secure loans from banking institutions. The exact point of bankability cannot be universally defined. Requirements for bankability vary between financing institutions and with market conditions. For example, risk appetite of banking institutions fell sharply after the financial crisis of 2008, see (Salmon et al., 2011), as a result the required proven generation capacity for lending increased significantly as well as the required of equity/debt ratio.

The feasibility study in the context of geothermal project development

A geothermal power project can be divided into a series of development phases before the actual operation and maintenance phase commences: preliminary survey, exploration, test drilling, project review and planning, field development, construction; as well as start-up and commissioning. In Figure 1 a schedule depicting the phases for a typical 50 MWe project, is shown. The lower graph shows the project risk profile and project cost at the different project phases.

The graph shows how the level of risk is reduced as the project advances. The highest risks are present during the early phases (Preliminary Survey, Exploration and Test Drilling) when there is considerable uncertainty regarding the characteristics and capacity of the resource. This uncertainty makes it difficult to know how much it will cost to extract the geothermal energy and to reinject the heat-depleted brine back into the reservoir.

Uncertainty is considerably reduced at the end of the Test Drilling phase. The test drilling and the subsequent production drilling² progressively confirm the resource availability. At some point the developer has enough information to decide on the field and project development strategy³. The project development strategy provides the premises for the feasibility study to be carried out.

The exact conditions for financing a project vary between finance entities. For example, commercial banks are known to put requirements regarding the amount of proven generation capacity before financing the power plant⁴. To finish the feasibility study, typically the developer is in contact with finance entities to agree on the financing conditions. The developer and finance entities jointly set up a funding plan including required capital structure (debt/equity) and amount of proven generation capacity in place for debt financing (see. Chapter 9). Two resources set the size of a geothermal power plant, the geothermal resource and the financing capacity.

The role of the feasibility study as part of the project development is therefore to secure financing when risk has been sufficiently reduced so that banking institutions consider lending to the project. The feasibility study is finished when the developer achieves financial closure for the project which means remaining project activities are financed, (see Figure 1). The remaining activities are typically the completion of the Field Development phase which includes the remaining production drilling and reinjection well drilling, construction of the steam above-ground system (SAGS), and the power plant.

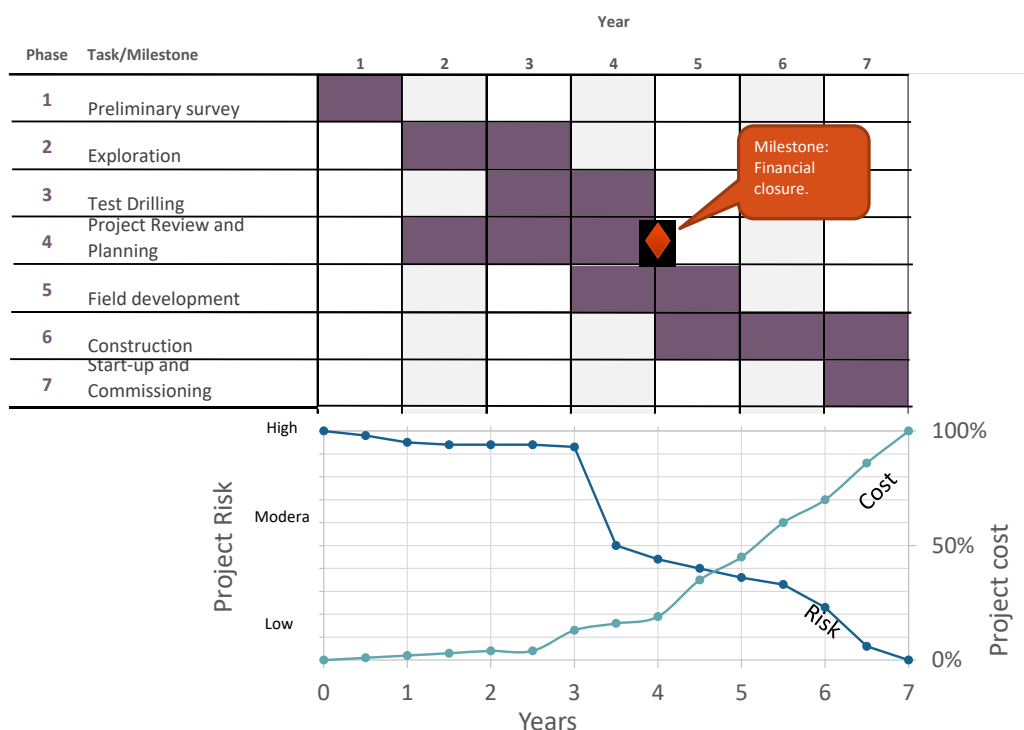


Figure 1. Geothermal project development phases (from ESMAP, 2012). Lower graph: Project Risk Profile and Project Cost at each Development phase (from ESMAP, 2016).

² The production drilling subsequent to the test drilling is sometimes referred to as confirmation drilling, delineation drilling or appraisal drilling.

³ The field development strategy includes decisions on how to develop the resource, i.e. generation capacity, whether it should be in stages or in one step, how many wells to drill and their location. The project development strategy also includes power plant and transmission lines capacity

⁴ ESMAP (2018) states that experience in Latin America and the Caribbean has shown that some commercial banks only consider offering financing for plant construction once at least 50 percent of the geothermal fluid required to fulfill the plant generation capacity is already available.

Content list for geothermal feasibility studies

Detailed industry standards for the preparation of feasibility studies in the geothermal industry have not been published⁵. A content list was compiled based on the authors' experience from the geothermal industry and by reviewing feasibility studies from other sectors and industries⁶. The proposed content list is as follows:

- Project concept and background
- Market concept and analysis
- Geothermal resource assessment
- Location and site
- Environment and social safeguards
- Engineering and technology
- Project execution plan and schedule
- Financial analysis and investment appraisal

In the subsequent chapters each item of the list above is discussed, and the corresponding content required for a feasibility study report explained.

2. PROJECT CONCEPT AND BACKGROUND

The first chapter of a feasibility study describes the basic project concept and background. The purpose of the first chapter is to provide a high-level overview of the scope of the project, its history and its context in the host country (on an economic, social and environmental level). The topics typically addressed in the Project Concept and Background chapter are:

- Project concept. A description of the project idea and major project parameters used during the preparation of the feasibility study is given. The scope of the project should be exactly defined and the project size in MW and investment explained. A description of the main systems and items of the project such as turbine-generator unit, cold end, steam gathering system and transmission lines, should be included as well as a brief description of the geothermal resource to be utilized.
- Project objectives. The principal objective is production of power, but the project may have other objectives as well (social, economic, environmental, technical). Side objectives could be a reduction in CO₂ emissions from the host country, job creation, and/or stabilizing of the electrical grid in a specific region of the country.
- Country objectives. Brief description of how project objectives fit into country national and sub-national objectives. The project objectives should be in harmony with the country objectives. Government policies that specifically support the project should be explained. This includes economic, social, financial and environmental policies.
- Geographical location. The project location should be shown on maps at an international, regional and local level. General information on permits, planning and zoning should be included here.
- Project developer description and organization. The name and address of the project developer, sponsors, partners, parent companies and other key stakeholders are presented. The technical and financial capabilities of the developer and key stakeholders, relevant to the project development, are described. In continuation of the description of the project developer and other stakeholders, basic information on the project organization, financing structure and other relevant characteristics should be given (joint venture, project financing, etc.)
- Brief project history. The historical development of the project including dates of essential events in development should be explained. The main studies and work performed to reach the current point should be listed as well as the main milestones and important decisions made on basis of existing studies and investigations.
- Purpose and intended audience. The purpose of the study and intended audience should be clarified. The author(s) and their titles within their respective companies should be given. This information could also be provided in the introduction to the feasibility study.

3. MARKET ANALYSIS - CONCEPT

A geothermal feasibility report needs to include an analysis of the energy market in the country in question as well as a description of the marketing concept proposed. It should e.g. address all key factors impacting the technical, legal and economic viability of the

⁵ IRENA has published a Bankability checklist accessible on <https://navigator.irena.org/> under IRENA Project Navigator - Technical Concept Guidelines for Geothermal Power. This checklist is broadly consistent with guidelines for feasibility studies provided in this report but with less granularity than presented here.

⁶ See for example (Behrens and Hawranek, 1991).

project involved and identify potential issues that could affect commercialization of the energy generated by the project, i.e. "market risk". The market risk is the risk that financial requirements will not be met during the financial horizon of the project due to market related reasons. The Market analysis and marketing concept chapter of a feasibility report should be dedicated to demonstrating that the market risk is sufficiently low to justify the project.

To evaluate an energy market, a comprehensive overview of that market is required, i.e. an energy market analysis. The energy market analysis should include information on:

- Description of the energy market in question, relevant regulations and who are the main stakeholders (generation, transmission, distribution and regulatory entities) and how the project fits to the market under the current conditions. A brief historical analysis presenting market statistics the last 10-15 years is appropriate. Known future changes to the energy market and their impacts should be described. This should include for example, projections of electricity demand, changes in regulations and generation expansion plans. Connections of the local energy market to other energy markets, for example in nearby countries, should be explained.
- Description of the conditions under which the energy will be sold. This should include all other contractual agreements related to the transmission and sale of energy. Of special significance is the contract for power sales, i.e. the PPA.
- Risks due to possible technical or contractual issues that can impede power sales from the developer such as transmission faults or power grid congestion should be described and evaluated. Note that it is always assumed that a power system study has been performed which analyses the technical compatibility of the power plant with the electrical infrastructure to which it will be connected. The power system study is further described in section 7.
- Review of fees and costs related to generation and sales of power, including all costs incurred through selling on the market as well as transmission cost (including system operation cost).
- If the developer needs to transfer currency to meet obligations outside the project country, currency fluctuation and currency convertibility and transfer risk needs to be considered as well.

In the market concept section of a feasibility study report, the premises for revenue structure over the project horizon is presented. This section also needs to explicitly discuss the market risk, i.e. the risk that the revenues of the project will be lower than expected, not due to lower production but because the developer does not get paid for the production as originally planned. Any risk that can influence revenue streams have to be treated in this chapter of the feasibility study report.

Long term energy sales. The most common way for the developer to deal with the market risk is to sell the energy with pre-defined rates either under a Power Purchase Agreement (PPA) with an off-taker or a Feed-In-Tariff set by authorities.

Power Purchase Agreement. In a PPA the off taker can be a utility, an industrial user or other entities in the country energy market. This converts the market risk into the contract risk of the PPA and the off-taker risk of defaulting. Information on the creditworthiness of the off taker must be presented in this section.

The PPA sets the contractual obligations of both the power seller and the off-taker such as prices, billing and payment and performance terms. It defines dispatch, operating and metering procedures, penalties for under delivery and procedures and manners of treating force majeure.

Feed-in-tariff. Many governments in countries with abundant of renewable energy resources have set a policy to encourage the development of renewable energy offering energy prices to developers based on a "Feed-in-tariff" (FIT). Such a policy requires a strong, long term commitment from the government and an elaborate legislative framework. Mandatory off-take of renewable energy by the power utility is a key element of FIT and a guaranteed energy prices set for number of years. With a FIT the market risk is eliminated with a government backed up energy purchases provided an adequate country risk profile.

Short term electricity markets. Another approach is to sell the energy on short term markets such as the energy spot market assuming such a market exists in the country where the project is located. If the revenue of the project will be obtained by selling the energy on a short-term market, a detailed risk analysis of possible market fluctuations over the project financial horizon must be presented. A sensitivity analysis must be carried out to assess how price fluctuations in the short-term market can affect the revenue stream of the project. Energy sales from the project proposed in the feasibility study can also influence the market. This must be considered in the analysis. Note that short term market prices can be influenced by a wide variety of factors. This can include the general economic situation of the country or the world as a whole or fuel prices which can influence the marginal cost of other generating units on the market.

4. GEOTHERMAL RESOURCE ASSESSMENT AND PLANNED RESOURCE DEVELOPMENT

This section gives an overview of the characteristics of the geothermal resource and its expected power generation capacity. Here, the results of resource exploration and drilling results along with production tests carried out to date are summarized and plans for drilling of the remaining wells are laid out. If the developer envisions a staged development of the resource, the plans for further development beyond the horizon of the project discussed in the feasibility study should be described. The key components of this section are:

- **The exploration history of the geothermal system.** The bulk of the surface exploration occurs before the feasibility study report is written, even though some additional exploration may be conducted throughout the development of the resource. An overview of the exploration work should be presented with reference to the main supporting documents. A guide to best practices in geothermal exploration was presented by IFC (2014). The feasibility study report should

demonstrate that the methodology followed has been consistent with what is considered best practice in the industry. The exploration drilling phase has also been completed, when the feasibility is prepared and typically some of the production drilling⁷. This section should provide a review of the drilling performed in the field, including basic well design information, well location and drilling targets, well success (including reservoir temperature and permeability intersected) and well productivity based on production testing data.

- **Conceptual model.** The results of surface exploration as well as the results of exploration drilling and testing, are normally presented as a comprehensive conceptual model of the geothermal system. Such a model is consequently used as basis for realistic development plans (to define drilling targets for remaining production and injection wells), but also as the foundation for energy generation capacity assessments⁸. The development and application of geothermal conceptual models are described in more detail in the text box below. The conceptual model should reflect the uncertainty in various parameters (e.g. reservoir volume, temperature conditions, etc.) that will affect the resource assessment.
- **Resource assessment.** The estimated generation capacity of the geothermal resource is the foundation of the decision regarding the size of the power plant to be developed in a given geothermal project. This section is, therefore, of a central importance in the feasibility study. The methods most commonly used for geothermal resource assessment are volumetric methods and detailed numerical models⁹. Two principal situations apply regarding the production capacity as presented in a feasibility study: 1) The generating capacity can be considered proven if predicted by an accurate and reliable (calibrated with the right comprehensive data) detailed numerical model (see below) and this is supported to some extent through testing of existing production wells. 2) If a reliable numerical model cannot be set up, the P90 outcome of a volumetric assessment (see below) is often used, but with more support from output testing of existing wells than in situation 1).

Volumetric methods are more suitable for providing a first order estimate of the resource capacity when production history is limited, whereas detailed numerical models are more appropriate where historical production data allows calibration of the models. As a result, the volumetric methods using probabilistic distribution of reservoir parameters and supported by observed well outputs are most commonly used for resource assessment in greenfield developments, i.e. where no production history data are available. The feasibility study needs to describe rationale behind the selection of reservoir parameters used as input parameters to the volumetric model and demonstrate how these are supported by direct observations from the field and the drilled wells. When results of volumetric resource assessments are used to decide the size of a geothermal power plant the P90 result¹⁰ is generally considered appropriately conservative.

Detailed numerical modelling results in more reliable estimates of generation capacity provided that the model is calibrated by comprehensive well test and reservoir response (e.g. pressure decline and interference) data. Numerical modelling is in such cases much more reliable than volumetric methods. Even though location specific, calibration usually requires testing for several months (about half a year or so). As well testing for such extensive periods is generally not practical for greenfield developments, resource estimates based on numerical models are almost exclusively used to determine the appropriate power plant size in expansion projects.

The principal factor controlling the production capacity of geothermal reservoirs is reservoir pressure decline (see Appendix B), which must be within manageable limits within the timeframe of the feasibility study. The following criteria is suggested in the case of initial development of a geothermal field (green field). If a numerical model predicts that the geothermal resource in question can sustain the planned capacity without too great pressure changes (<10 – 30 bar, depending on thermodynamic conditions), with manageable temperature changes and well-output decline that would result in a financially viable need for make-up wells, then the exploitation can be maintained throughout the time-frame of the feasibility study. For a geothermal field where some development and production has already taken place, somewhat greater predicted changes (mainly in pressure) may be acceptable in some cases.

- **Proven capacity or steam at well head.** A key component of a geothermal feasibility study is an explicit statement of the proven generation capacity of the wells drilled at the time of writing the feasibility report. Lenders typically have specific requirements as to how much of the planned generation capacity is proven through well tests at the point of financing. The exact requirement of proven generation capacity varies between lenders and market conditions. A commonly cited value is 50% of the planned generation capacity but this is known to vary between 25 and 80% (NREL, 2011). Once 50 to 80% of the generation capacity are proven the financing risk is considered comparable to that of gas-fired power plants (NREL, 2011). The proven capacity is typically presented as the cumulative output, either in kg/s of steam at a specific well-head pressure or in MWe determined through discharge tests. This section of the feasibility should describe the discharge tests and show the results. It is particularly important to demonstrate to lenders that the wells had

⁷ Drilling that immediately follows exploration drilling is sometimes referred to as appraisal drilling, confirmation drilling, or delineation drilling. The wells drilled during this phase are typically designed to be used as production wells.

⁸ Volumetric resource assessments, numerical models and other simpler models, should be based on the conceptual model.

⁹ These, and other assessment methods (modelling methods) are described in Appendix B: Resource assessment.

¹⁰ A probabilistic volumetric model will result in a probability density function representing the range of possible generation capacities, resulting from assumed parameter ranges or distributions. In this context the estimated P90 capacity represents the generation capacity equals or is exceeded by 90% of the estimated generation capacities resulting from the model.

reached as stable, or semi-stable condition during the test and the cumulative output capacity reflects stabilized well conditions. This section is sometimes supported by a resource assessment report prepared by external experts.

- **Field development plan.** The feasibility study should include a detailed field development plan that shows where the remaining production wells and reinjection wells for the planned power plant will be drilled. The motivation for the well locations should be based on the conceptual model for the geothermal system. The development plan should also explain in detail the reinjection strategy. ReInjection of the geothermal fluid is most often a requirement of environmental permits but is also a key factor for the long-term operation of the geothermal field. The reinjection strategy is often developed through a trial and error approach involving comprehensive investigations (e.g. tracer testing) and highly site specific because it depends on the details of the reservoir structure. The reinjection strategy should be part of the exploitation plan from the onset of the project. Options should be presented regarding reinjection with reference to the conceptual model explaining the likelihood of providing pressure support with the reinjection strategy.

The field development plan must assume >100% success rate of geothermal well drilling (see IFC, 2013). There is always a certain probability of failed wells when drilling into a geothermal reservoir. The field development plan should include a provision for a reasonable number of unsuccessful wells, as a contingency. The number of wells and their characteristic should be included in the development plan so that the cost estimates for production drilling can be included in the project implementation budget in section 9. Time of drilling should be included as wells so that this can be included in the schedule. Drilling of make-up wells to compensate pressure decline in the geothermal field should also be included in the field development plan.

Note that the locations of the wells that remain to be drilled at the time of preparing the feasibility study, are not exactly known. The reason is that as results from the wells become known, the locations of subsequent wells can be changed. The field development plan is therefore up to a certain point a dynamic document until the production and reinjection drilling is completed.

Conceptual models

The key to successful exploration, development (including drilling) and utilization of any type of geothermal system is a clear definition and understanding of the nature and characteristics of the geothermal system. This is generally achieved through the development of a conceptual model, i.e. a descriptive (qualitative) model incorporating, and unifying, the essential physical features of the system. Conceptual models are mainly based on analysis of geological and geophysical information, temperature and pressure data, information on reservoir properties as well as information on the chemical and gas content of reservoir fluids. Monitoring data reflecting reservoir changes during long-term testing and exploitation, furthermore, aid in revising conceptual models once they become available. Conceptual models should explain the heat source for the reservoir and the location of recharge zones, the location of the main flow channels, the general flow patterns within the reservoir as well as reservoir temperature and pressure conditions. A comprehensive conceptual model should, furthermore, provide an estimate of the size of the reservoir involved. Conceptual models are developed through interdisciplinary cooperation between geologists, geochemists, geophysicists and reservoir engineers involved in the geothermal project development. Conceptual models are an important basis of field development plans, i.e. for selecting drilling sites and targets of wells to be drilled. The conceptual model is also the foundation for all geothermal resource assessments, particularly volumetric assessments and geothermal reservoir modelling, used to assess the energy production capacity of a geothermal system. Initially a conceptual model is mostly based on surface exploration data, but once the first wells have been drilled into a system and subsurface data become available the model is updated. The most important information obtained by drilling are the locations of feed-zone, temperature profiles and well-test data. Conceptual models should be revised, and improved, continuously throughout the exploration, development and utilization history of a geothermal system, as more data and information become available.

Further field development plans

A common strategy in geothermal development is to develop the resource in phases. This means that instead of building a power plant for the whole resource at once, the generation capacity is built up in phases. This can reduce the risk of the development as experience is gained in the partial exploitation of the resource before a decision is taken on adding generation capacity. If the project presented in the feasibility study report is part of a multistage development, this must be carefully explained in the field development plan. A multistage development has many advantages in terms of risk reduction. It reduces substantially the risk for future capacity estimates as data from the ongoing exploitation of the reservoir will be available to calibrate numerical models of the reservoir generation capacity.

5. LOCATION AND SITE

Location and site refer to the geographical placement of the project. In a feasibility report, project aspects related to the location and site of the project are described and critical characteristics summarized. A distinction is made between location and site. Location can refer to a wider geographical area where it is expected that the geothermal resources can be found. Site, on the other hand, refers to a specific place within the location area where infrastructure such as wells and power plants will be placed. The site is usually selected after several options have been evaluated within the project location.

Note that unlike most other industrial projects, the location of a geothermal project is linked to the geothermal resources. Geothermal projects are therefore often located in remote places with poor access and infrastructure. For this reason, it is important to explain carefully how the location affects the project.

Excluded here are environmental, social and legal aspects related to the location as these are treated specifically in the section on Environmental and Social Safeguards.

In what follows, a summary of the main location and site aspects relevant to geothermal projects is given.

- Natural environment. A description of relevant climate conditions, namely temperature, rainfall, humidity, wind, snow, dust and solar radiation should be a part of the chapter on Location and site.
- Natural hazards. Estimation of risk of natural hazards such as floods, earthquakes, volcanic eruptions and hurricanes impacting the project should be presented. This is often done with maps showing distinct zones of higher and lower risk.
- Geotechnical aspects. Geotechnical aspects are of importance to site selection as these can cause important cost increases if not carefully investigated. These can include soil conditions and subsoil water levels.
- Existing infrastructure condition and access. Geothermal projects are sometimes located in remote places. For this reason, it is important to explain conditions of roads on transport routes for heavy equipment to the site. This can also include harbour infrastructure for sea transport. The main distances equipment will be transported should be indicated. Access to water and electricity and for the distinct project phases should be explained. During construction and operation, availability of human resources for the distinct project phases must be guaranteed. Furthermore, availability of services such as civil construction, equipment installations and maintenance for the distinct project phases should be clarified.
- Maps. Location and site issues should be demonstrated on maps to enhance clarity. To make orientation easier when reading maps, population centres and/or other landmarks should be shown as well. Existing and future infrastructure to be built should be clearly distinguished on the maps.

All the above-mentioned issues should be described in a feasibility study report. If any specific issue has considerable impact on project risk, mitigation efforts to avoid harmful effects should be described as well as impact on cost or time schedule.

Costs related to location issues should be identified and quantified. This can include cost related to site preparation and cost due to risk mitigation efforts.

6. ENVIRONMENTAL AND SOCIAL SAFEGUARDS

All geothermal projects have associated environmental and social impacts and risks. Management of these impacts and risks is critical for the successful development of geothermal projects. A chapter in the feasibility study report should be dedicated to demonstrating that environmental and social impacts are assessed and managed in a way that reduces the risks associated with environmental and social issues to an acceptable level. Inappropriate handling of these issues can result in the termination of the project, delays and/or costly mitigation measures later in the project.

Best practices

Developers seeking international financing should adopt international best practices to identify and address environmental and social impacts and risks¹¹. Requirements in host countries must be followed as well and therefore a gap analysis should be presented in the feasibility study report to demonstrate that the project fulfils both local and international requirements. The gap analysis systematically lists the local and international requirements and highlights the differences (gaps) between the two, if any. The most widely accepted best practices that are typically applied are the Equator Principles¹², the IFC Performance standards¹³. The recent World Bank Environmental and Social Standards¹⁴ will apply to future projects financed by the World Bank.

Project maturity

At the time of the feasibility study report, all necessary processes to obtain licences should be finished and most, if not all, permits should have been obtained for the power plant. For any permit or licence that has not been obtained, clear low risk paths to obtain them must be presented. A typical geothermal project generally has significant environmental impacts. This is sometimes referred to as category A project¹⁵. As a category A project an Environmental and Social Impact Assessment (ESIA), covering all important aspects as required by PS1 in the IFC Performance Standards, must be submitted and processed with all relevant key stakeholders, including the local community, Project Affected Persons (PAPs), an environmental authority and other issuers of authorization or licenses.

¹¹ In (ESMAP, 2018), international best practices for mitigating environmental and social risks in geothermal projects are presented. This chapter is partially adopted from that reference.

¹² <http://www.equator-principles.com>

¹³ <http://www.ifc.org/performancestandards>

¹⁴ <https://www.worldbank.org/en/projects-operations/environmental-and-social-framework/brief/environmental-and-social-standards>

¹⁵ Category A projects are those likely to have significant adverse environmental impacts that are sensitive, diverse, or unprecedented. These impacts may affect an area broader than the sites or facilities subject to physical works. See (World Bank, 2018).

Environmental and Social Impact Assessment (ESIA) (from (World Bank, 2018))

The predominant international standard mechanism used to identify and manage environmental and social impacts and risks is the ESIA. The developer sponsors the ESIA, but it is generally carried out by an independent party with appropriate expertise. Most countries require only an EIA be prepared for infrastructure investments. A more in-depth ESIA usually meets national requirements, but the scope and breadth of the ESIA is wider and deeper than most national EIA requirements. An ESIA also identifies the extent and complexity of potential social impacts and the socio-economic characteristics of people in the project area. It comprises the normal contents required by a national EIA, in addition to four additional components that have gained traction over the last two decades through the convergence of the policy requirements of various international agencies: i) Environmental and Social Management Plan (ESMP), ii) Stakeholder Engagement Plan (SEP), iii) grievance mechanism, and iv) community health and safety plan. If the ESIA is carried out to supplement or update a previous EIA/ESIA, it will include an Environmental and Social Action Plan (ESAP) that assesses the content and implementation of previous efforts taken to identify deficiencies and to plan actions to bring the process up to international standards. Finally, standalone land acquisition and resettlement documents and/or an indigenous peoples' development framework or plan may also be required, as appropriate.

Because of the nature of geothermal reservoirs as dynamic resources it depends on each case how realistic it is to have a final understanding of all aspects of the project and its impacts at the feasibility stage. At the point of feasibility, several wells still need to be drilled, and it is not unusual that their location is not exactly known at the time of writing the feasibility study report. The final design of the steam gathering system and reinjection pipelines cannot be finalized before the final well locations have been decided. Therefore, while the location of the project is clear, the exact layout of all the steam field facilities may not be defined at this stage. Further production drilling may have to be carried out on the resource before all location specific impacts can be described and assessed. In projects where this is the case an Environmental and Social Management Framework (ESMF) may be appropriate.

However, it must be emphasized that the ESIA should be as comprehensive and implementation-ready as the knowledge of the geothermal resource and status of design allows. At a minimum, a sectoral - or a strategic environmental assessment should be provided where uncertainty still exists on layout, location or design with information on how the ESIA/ESMP will be updated once relevant information exists. If further permits will be needed, a clear, low-risk, path towards obtaining all permits necessary must be established in the feasibility study report.

Environmental and social risks and impacts

In (World Bank, 2018), typical environmental and social risks and impacts are grouped into twelve principal categories. The categories are described in Table 1.

Table 1. Environmental and social risks and impacts in geothermal projects (from (World Bank, 2018))

Environmental Impacts and Risks

- **Land and habitat loss.** Many new developments occur in remote areas with volcanic characteristics yet can take place in areas that are already in use and populated. The implications of remoteness include: (1) small local populations, (2) the need for promoting access by constructing new or improved roads leading to and around the site, and (3) an increased likelihood of being either near or within critical habitats or protected areas. Despite having a limited footprint, a new facility can disrupt local use and livelihood patterns that are dependent on crop or animal production—especially when the land is used by indigenous peoples. In some areas, local concerns about perceived risks (not always real or founded) that geothermal development may cause landslides, seismicity, and disturbances from natural hydrothermal manifestations, may lead to resistance to geothermal development in local populations.
- **Water risks.** This category includes water use and quality. Well drilling, stimulation, and testing require surface and underground water that could pick up dissolved minerals and can pollute surface and ground waters if not managed carefully. Similarly, water used to clean the facilities may add contaminants, and leaks from breaks in well casings can contaminate groundwater. Surface and underground water requirements vary at different stages of development and operation, from drilling to managing the geothermal resource and cooling. The relative abundance of nearby water sources and the level of competition for their use determines the level of risk.
- **Solid discharges and waste.** Drilling muds are generally recycled and reused, but the cuttings can contain hazardous components such as sulfides, arsenic, mercury, nickel, and other heavy metals, which can leak into the environment if not managed and disposed of properly. Holding ponds constitute a public hazard if not protected from unauthorized access.
- **Gas emissions.** The principal non-condensable gases (NCG) encountered in geothermal development are carbon dioxide (CO₂) and hydrogen sulfide (H₂S). In some cases, mercury (Hg) can be present in low, but significant, amounts in the NCG. NCG are released at well sites in site development and afterwards. During operation, the NCG is carried with the steam from the well, passes through the steam turbine, where the water vapor is condensed, and is released through venting. NCGs can be captured and treated for commercial purposes or injected back into the sub-surface, but injection of NCGs is not a common practice. H₂S, in particular, has an obnoxious smell even at low concentrations and poses a health hazard if concentrations are high. Some jurisdictions require that H₂S and Hg be removed from the geothermal NCG through chemical treatment.
- **Dust and noise.** Noise pollution from geothermal is especially prominent during well drilling, stimulation, and testing phases and during construction of the powerhouse and related facilities. The operation of the transformer, power house, and cooling towers add noise to the environment, depending on design. Construction machinery and trucks for the facilities also increase noise and dust in the project area.

- **Occupational health and safety.** Employees at geothermal drilling and operation facilities face various occupational risks to their safety, ranging from well blowouts to pipeline failure and seismicity issues and impacts. Some of the impacts and risks can be mitigated by having a robust regulatory framework that includes health and safety standards or requirements (for example, one that requires geothermal companies to put in place and adopt standard industrial safety practices in the field). Other risks that are specific to geothermal, such as the risk of encountering toxic fumes in a closed area, can be addressed by requiring companies to adopt standard industrial health and safety practices, such as management plans to mitigate this risk that include emergency response measures.

Social impacts and risks

- **Livelihood and ecosystem services.** Land acquisition or loss of access to land due to geothermal development can impact the livelihoods and everyday lives of local people. Regardless of whether the land is owned by individuals, communities, or even the state, if people are dependent on it for livelihoods or resources that they use consistently, the loss can be difficult to overcome, even if the users are compensated by relocation, cash, or land swaps. The severity of the risk varies, with vulnerable and indigenous peoples most at risk.
- **Disruption.** Drilling, testing, construction, operation, and decommissioning can disrupt family and community life with increased traffic, influx of labor, and damage to assets and resources. This can have consequences for health and safety, as well as peace of mind.
- **Conflict.** New facilities and investments, including land purchases, bring new opportunities to communities, but also disruptions and competition over access to employment, commercial opportunities, and ownership of new resources. Such changes can renew long-standing kinship or clan conflicts or create new ones based on gender, generation, or other factors.
- **Cultural heritage.** New geothermal developments can take place in or near sites that are protected or prized for cultural significance or aesthetic aspects, threatening or compromising the physical or visual status of the site. Nationally or internationally recognized cultural assets generate much interest, but even sites of local importance require special attention.
- **Apprehension and opposition.** In addition to the social impacts and risks caused by the objective factors described above, geothermal investments can cause local people to be apprehensive or suspicious, based on real information about poorly-managed developments in other areas, rumours, misunderstandings, or fear of the unknown. Such apprehension can generate local opposition, which may be nurtured and amplified by external interests.

Environmental and Social Safeguard topics in Feasibility Study Report

The topics that a feasibility study report should address in the chapter on environmental and social impact are the following:

- **Legal framework, processes and institutional capacity.** An overview should be given of the legal framework in the host country to the project. This should include information on institutional and regulatory frameworks and licensing procedures. An overview of the issuers of licenses and the institutional capacity within expert agencies will provide further insight into the regulatory environment of the project.
- **Gap analysis.** For internationally funded projects it is important to provide a comparison between national legal requirements and international best practices such as the Equator Principles and the IFC Performance Standards and of how any gaps are addressed.
- **Current status and previous work.** For geothermal projects, the environmental licensing is done in phases: a) exploration phase(s), and b) development/construction and operational phase. Information on previous processes and licenses during exploration are an important part of this overview. Furthermore, if the resource is developed in phases, licences and permits obtained in earlier phases should be explained.
- **Relation to other project activities.** It is important to demonstrate that the environmental and sociability feasibility work has been carried out in parallel with the technical development of the project and that all technical and/or economic aspects are considered in the environmental impact assessment work.
- **Main results of the ESIA.** Results of an environmental and social impact assessment shall be described in the feasibility study report. The ESIA should provide a clear project description and description of the current environment of the physical, biological, socio-economic, and cultural components of the site and areas of influence. Based on this information an assessment of the possible impacts of the project shall be provided, a description of actions to avoid, reduce or compensate for such impacts and actions proposed for monitoring and management of environmental and social aspects. The ESIA should cover all relevant aspects of biodiversity conservation and sustainable management of living natural resources, indigenous peoples, other vulnerable groups, cultural heritage. Cumulative impacts should also be considered. Furthermore, if a part of the energy infrastructure, such as transmission lines, is not in the developer's scope then they should still be included in the ESIA of the power plant.
- **Access to land.** An overview of land ownership and use should be provided. Information on land acquisition processes, land use restrictions and status of land use zoning if relevant. According to the World Bank Environmental and Social Framework (ESF) Environmental and Social Standard 5 on Land Acquisition, Restrictions on Land Use and Involuntary

Resettlement, PAP's who do not hold a formal legal title to land are also eligible for benefits. This is in many cases beyond local requirements on eligibility for benefits.

- **Stakeholder engagement.** Information on past, ongoing and planned stakeholder engagement, i.e. Stakeholder Engagement Plans (SEP's) and Community Development Frameworks (CDF's) if relevant for the project.
- **Tasks and timelines.** The document should show the estimated timeframes for ongoing and remaining tasks of the ESIA work. This can be tasks such as landowner negotiation and acquisition of land (Resettlement Policy Frameworks and Resettlement Action Plans if applicable), environmental and social baseline research, ESMP's, Stakeholder Engagement and CDF's, statutory presentation and review periods, licensing processes and monitoring programs.
- **Responsibility for the implementation of mitigation measures and associated cost.** Information on who is responsible for the implementation of mitigation measures and estimated cost of mitigation measures should be provided. This includes both cost during development phase and operation phase.

7. ENGINEERING AND TECHNOLOGY

The scope of the engineering and technology section of a feasibility study report is to present the functional aspects and physical layout for the geothermal power plant. Other technical infrastructure such as the steam gathering system, wells, transmission lines and substation infrastructure should also be included. This section should include a discussion on the choice of technology for power generation, the basic engineering design and a cost estimate that is used in the financial analysis.

In the ESMAP Geothermal Handbook (ESMAP, 2012), information regarding common choices of power generation technology in the geothermal industry can be obtained. This document can be used to show how the information presented on technology choice in the feasibility study compares to benchmarks in the geothermal industry.

The objective of the section on engineering and technology in a feasibility study report is to demonstrate that:

- The power plant can and will be designed and built according to the project criteria, adequate standards and good practices.
- What the capital costs of the plant are to be considered in the financial analysis.
- The power plant will operate reliably, enabling the owner to meet contractual obligations in terms of power sale.

Project maturity. The recommended practices of AACE for cost estimate classification, see (AACE, 2005), give important guidelines regarding what level of maturity the cost estimate and the engineering design should have reached for a feasibility study report. For a feasibility study, a class 3 estimate, according to the Cost Estimate Classification System of the AACE, is appropriate.

At the time of preparing the feasibility study the engineering design should be at the starting point of detailed design. After the financing is secured, typically the detail design phase would begin.

In what follows, the topics and the deliverables of the engineering design that should be included in the feasibility study report are discussed.

Main technical parameters. The main technical parameters and boundary conditions of the power plant should be clearly presented. If these are presented in other sections of the report, clear references should be given to these other sections. This includes the plant capacity as many of the performed studies related to the feasibility study (resource capacity, grid studies etc.) are performed with a fixed capacity in mind. A description of the boundary conditions for the plant should be included. This includes for example the assumed geothermal fluid chemical composition, its NCG content, and any other aspects that can influence the choice of the technology. These factors can introduce risks to projects that the feasibility report shall identify and demonstrate how the risks will be mitigated. For example, scaling and corrosion potential of the geothermal fluid can be analysed from its chemical content.

Technology choice and equipment selection. The choice of technology shall be motivated given the resources characteristic and clearly presented. The risk of inappropriate technology choice must be shown to be minimal by explaining that the technology selected is not risky and will perform with adequate efficiency. This can be done by identifying the available and commercially accepted power cycles for the main technical parameters. Technical proposals from known vendors of geothermal power generating equipment should be obtained to demonstrate in the feasibility report what power output can be expected given likely resource parameters such as steam flow and enthalpy. These numbers should be compared to publicly available publications such as the ESMAP (2012) Geothermal Handbook, which presents the most common technology choices for geothermal power plants.

Specific equipment selection should be explained in a similar way as technology choice. Main suppliers should be mentioned and important aspects such a procurement lead time should be summarized.

Basic engineering. As previously mentioned, it is assumed that the maturity level of engineering has been reached but not entered the detail design phase when the feasibility study report is prepared. The basic engineering on the other hand has been completed when the feasibility report is written.

The basic engineering should be presented for the technical systems entailing the biggest cost of the project. This includes at least the power plant, steam gathering systems, wells and transmission infrastructure. The basic engineering is presented with a system description and a set of design documents attached to the feasibility study report.

As also previously discussed, the maturity level is intrinsically related to the required accuracy of the cost estimate. A feasibility study should have reached class 3 according to the AACE cost estimate classification scheme¹⁶. This is in accordance with the required maturity level of feasibility studies in other industries, see (Behrens and Hawranek, 1991). The AACE present guidelines for the level of maturity of the engineering design for a class 3 cost estimate. The following design document should be completed and presented in the feasibility study, at least in a preliminary version:

- process flow diagrams with heat and mass balances,
- utility flow diagrams,
- preliminary piping and instrument diagrams showing the main pipe diameters and the material selection for pipes.
- layout drawings and plot plans,
- a single line diagram showing the plant and connection to existing grid infrastructure,
- process and utility lists of main equipment.

The basic engineering description and documents define the scope of the project. Scope limits showing boundaries of the areas of responsibility in the project should be included in the design documents as appropriate.

A summary of the most common design criteria should be presented. This should consider the natural environment such as natural hazards and other relevant conditions due to the locations of the plant. The design codes with respect to earthquakes, wind load etc. should be mentioned.

For geothermal projects, scaling, corrosion and NCG content pose special risks that should be addressed in the basic design description and documents.

Maintenance and operation characteristics. Characteristics in terms of operations should be described, namely level of automation required, number of personnel present during typical operation (night and day), typical availability (counting planned and unplanned stops for maintenance or other). Note that availability of the power plant is an important input parameter in the financial modelling.

Power system study. To connect a power plant to existing electrical infrastructure, a power system study (sometimes called a grid connection study) is performed to analyse and simulate the grid behaviour with the plants added to the grid. This demonstrates the feasibility that the power plant can be integrated with the existing electrical infrastructure to which it will be connected. A summary of the results of the grid study should be included in the feasibility study report.

Civil works. The feasibility study should provide plans and cost estimates for the civil works related to the project. This should cover site preparation and development, buildings, civil engineering works relating to utilities, transport, emissions and effluent discharge, internal roads, fencing and security, and other facilities and requirements of the plant.

Cost estimates. Proportionally the biggest part of project cost is due to the power plant and related infrastructure such as wells, steam gathering system and electrical infrastructure such as transmission lines. As previously discussed, the cost estimate should be of class 3 according to the AACE cost estimate classification scheme.

The purpose of the cost estimates is to demonstrate that project cost is reasonable. Comparison with cost bench marks from for example the ESMAP geothermal handbook should be included¹⁷. Any major divergence from industry benchmarks should be explained.

Cost estimates become obsolete with time. A common practice when using older cost estimates for comparison is to use capital cost indices such as the Chemical Engineering Plant Cost Index (www.chemengonline.com) to update estimates.

The capital expenditure cost (CAPEX) should be presented in itemized lists showing the main quantities and unit costs. This includes cost estimates for all main items such as power plant, steam gathering system and wells. Transmission lines and substations should be included as well when part of the scope of the project. These itemized lists should be presented in such a way that a check of consistency between them and the basic design documents can be easily performed. It should be easy to verify that all important items included in the scope of the project are accounted for in the cost estimate.

The cost estimate methods should be explained. Experience from other projects should be specifically denoted. For high cost items, preliminary tendering should have been performed to obtain budgetary proposals including delivery time estimates from the main suppliers.

Both direct and indirect cost should be included in the cost estimates. Engineering and supervision cost should be counted separately.

¹⁶ Class 3 of the AACE cost estimate classification scheme is similar to requirements on cost estimates in feasibility studies from other sectors, see (Behrens and Hawranek, 1991) where the required cost estimate accuracy quoted is $\pm 10\%$.

¹⁷ Country to country cost variations should be considered in this comparison.

The operating expenses (OPEX) should in a similar way be clearly presented in itemized lists. Of special importance is to present assumptions regarding drilling of makeup wells during the project financial horizon. All costs that are incurred due to operation and maintenance of technical systems during the horizon of the financial modelling should be listed in this chapter so that they can be compared with the technical descriptions of these systems given earlier in the chapter. This should include cost of manpower to run plant and workshop and cost of spare parts.

Finally, the assumptions regarding cost contingency should be explained in a clear and concise manner. This should include cost due to unsuccessful wells in any remaining drilling campaigns.

8. PROJECT EXECUTION PLAN AND SCHEDULE

The project execution plan describes how the project will be executed during the project implementation period. This is the period from the decision to invest to the start of commercial production. The project execution plan should also contain how the execution will be managed by the project developer by providing responsibility matrixes and organizational charts that describe the management structure.

The project time schedule shows how the project tasks are positioned in time. The purpose of this section is to demonstrate that the project has been carefully planned and therefore, risks related to budgeted cost and schedule have been minimized.

Professional project management is key to optimal execution of the project. Modern project management involves effective preparation, planning, analysis of risk aspects and risk management, procurement, execution, project control and contract management. Several entities have suggested versions of best practices in project management, but none of these methods has emerged as the dominant method across the board (see e.g. (Project Management Institute, 2017)). Effective project management ensures a comprehensive overview at all stages of preparation and execution and makes it more likely that individual project components and the project in its entirety remains within the defined time and cost frame. The project execution plan should contain a description of the project management methodology that will be applied during the project execution.

WBS and schedule. The project execution plan should above all include a description of the Work Breakdown Structure (WBS) of the project and a description of the stages of the project, all combined in a project schedule. The WBS and the schedule should include:

- A clear description of the scope of the tasks in the WBS with clearly defined milestones and deliverables as needed.
- Determination of the logical sequence of tasks and milestones.
- Demonstration of the critical path of the schedule which demonstrates which tasks will directly influence the project timeline if delayed.
- It is desirable that larger tasks should at least be broken down into Engineering, Procurement and Construction. This includes for example, the power plant and steam field engineering and construction as well as engineering and drilling of the geothermal wells.

The project schedule should have reached class 3 or 4 of the AACE schedule classification system.

Project implementation budget. An implementation budget should be presented in this section showing the cash flow as a function of time during the project execution phase. The purpose of this is to show the link between the WBS and cash flow and demonstrate that adequate funds will be available throughout the project execution phase. Note that this does not only include the CAPEX cost but also the cost of running the project through the development phase.

The implementation budget is an important input into the financial analysis of the project.

Other project execution issues. Other important aspects of project execution are listed to be included in a feasibility study report. Some of these are:

- Organization description of the project development company. This includes:
 - Organizational chart and the personnel involved in project execution.
 - Human resources according to categories and functions. The execution of a complex project requires an experienced and competent team.
 - Overhead cost of the project execution company.
- Procurement and contracting strategy. This should include a description of the scope of the main procurement packages, what packages will be procured locally and internationally and a high-level description of the tender process that will be applied to guarantee competitive bids. Contracts regarding drilling and EPC of the plant should be in place.

9. FINANCIAL ANALYSIS AND INVESTMENT APPRAISAL

An essential part of any feasibility study report involves financial analysis of the project. Financial analysis for a geothermal project follows the same principles as for other energy projects. However, high upfront development cost and resource risk makes financial structuring different.

The objective of the financial analysis is to demonstrate that the project will have a sound financial basis considering the project development cost, all commitments of the developer such as environmental and social measures and deliver acceptable returns to the developer while servicing the debt of the lending entity. It is on the results of the financial analysis that the decision to finance a project is made.

Financial model. A financial model is created whose main inputs are the cost, revenue and time horizon of the financial planning. The output are the parameters reflecting the financial return. They are calculated with formulas based on discounted net cash flow of the project.

Financial modelling based on the discounted cash-flow concept is generally accepted as a methodology for investment appraisal. The cash inflows and cash outflows over the financial planning horizon are estimated. Net cash flow is the inflow minus the outflow. Figure 1 shows a typical net cash flow over the financial planning horizon. It is negative in the beginning during the development phase while in the operation phase it is positive as the plant generates revenue with the power sales. A typical financial planning horizon for a geothermal energy project is 30 years (5 years for the development phase, 25 for the operating phase), see ESMAP (2012).

Two cash flow scenarios are generally analysed. The first one considers project cash inflows and outflows. This includes as outflows the sum of the project implementation budget (which in turn includes CAPEX), OPEX and production losses if any. Cash inflow is the sum of sales revenue, revenue from selling assets if any and recovery of salvage value (end of project).

The other scenario considers only net cash return on equity. This reflects the financial return of the project to the project developer. In this case, the cash flows associated with loans, grants, subsidies are subtracted from the project net cash flow. Outflows connected to loans are interests and amortization of loans and repayment of grants.

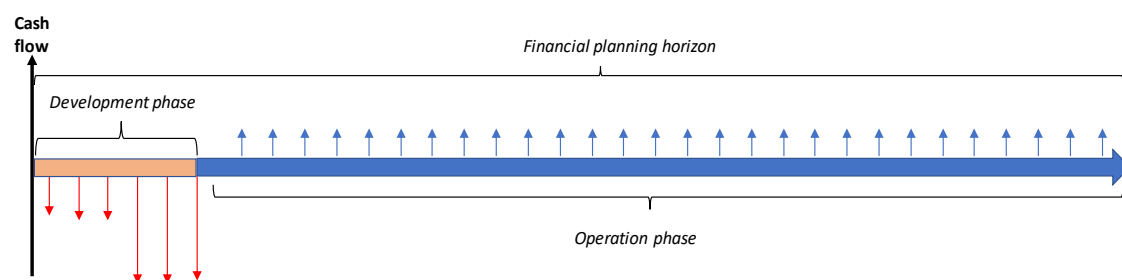


Figure 1. Cash flow over a typical 25-year financial planning horizon.

Financial model inputs. Several of the inputs to the financial model are discussed in the previous sections of the feasibility study report. This includes the CAPEX and OPEX and how these parameters are distributed over the financial horizon. The distribution of the CAPEX over the development phase is presented as the project implementation budget in Section 0. The premises for revenue structure are discussed in Section Error! Reference source not found..

Financial model outputs. Typical financial model outputs that are calculated using the cash flow over the financial planning horizon are Net Present Value (NPV) and Internal Rate of Revenue (IRR). Several other can be mentioned as common for the financial appraisal such as Return On Investment (ROI), Return On Equity (ROE), Debt-Equity ratios and Debt Service Coverage Ratio – DSCR.

Financial model presentation. The financial model needs to be presented in a thorough way in the feasibility study report. Typically, it is presented in tables showing in detail how the distinct items are calculated. Tables should include accounting statements for the financial planning horizon presented in the form of:

- balance sheet;
- income statement;
- cash flow statement;

The financial model outputs values should be clearly demonstrated as well as the way in which they are calculated with reference to the tables above.

Several assumptions are always made when creating the financial model. These should always be clearly presented. Accounting methods must be clearly explained and those not in line with Generally Accepted Accounting Practices, GAAP, must be explained in detail.

The following aspects should always be explained as part of the presentation of the financial model.

- Finance and loan structure. It is quite common that several sources are used to fund a project. The finance structure should be explained in a transparent manner showing amounts, payment conditions such as grace period and interest rates.
- Amortization schedule.

- Review of all taxes and tax credits if any.
- The way inflation is treated in the model.
- Weighted average cost of capital (WACC)
- Insurance structures used to transfer risks.
- Exchange rate assumptions if applicable.

Funding Plan.

Knowing the generation capacity of a geothermal resource with sufficient certainty, i.e. when the available capacity estimate can be considered proven (see chapter 4), will improve the possibility of commercial financing of a geothermal project. But projects usually seek financing well before 100% of the steam the power plant will require, has been secured, or proven. The term “steam behind the pipes” is sometimes used, meaning a proven resource in terms of financing; in essence steam at well head ready to be used.

Geothermal projects require having a sound Funding Plan in place, in line with how much resource needs to be proven as “steam at wellhead” when external funding can be achieved. This means that initial steps of geothermal development (exploration, concept design and part of production- and reinjection drilling) must be funded by developer, that is with equity or soft finance. This means that the financial strength of a developer can determine the generation capacity of a power plant or phases the plant to be built in. The Funding Plan is set in cooperation with the providers of external debt as they will require certain share of the energy resource to be proven when external funding is provided either debt or equity.

A development plan is then linked to the amount of proven resources where it is determined when certain activity can start, based on when a developer is certain that the knowledge on characteristics of the resource will not change. This has to do with activities such as deciding on potential plant capacity, business plan, energy sales and transmission, concept design, detail design, tendering, and procurement. For some geothermal energy development projects half of the resource required needs to be proven before detail engineering design starts. A clear definition shall be provided in the funding plan regarding at what resource milestone certain activity can start and who makes that call, based on what data.

The Funding Plan is a framework agreement between the developer and providers of external funding. The plan forms the basis of the feasibility study and sets the key parameters in terms of generation capacity of power plant aimed for and milestones to be reached to unlock external funding. The Funding Plan should be clearly presented in a feasibility report. Of critical importance is a clear presentation of the funding during the development phase. This can be achieved by including a Capital Deployment Table covering the development phase.

Capital Deployment Table. A critical aspect of geothermal projects is the high funding requirement during the development phase. Delays during this phase have a significant impact on the financial outcome of the project. The risk of running out of funds during this phase is also important and to have this aspect as clear as possible, a capital deployment table should be created showing sources and uses of capital for each quarter during the development phase. How the money is used is partially demonstrated in the project implementation budget but in the capital deployment table, the granularity in time is finer and it shows interest payments, fees and any other cost incurred as loans are added as sources of capital. On the sources side, the provision of equity, grants, loans and any other funds during the development phase is shown. The capital deployment table demonstrates drawdown of debt and drawdown of equity during the development phase.

Sensitivity analysis. The influence of uncertainty in financial input parameters on the financial outcome parameters is investigated by performing a sensitivity analysis. The objective is to demonstrate that the financial outcome of the project is robust towards these uncertainties. This means that even in presence of uncertainty, the values of the financial output parameters will always be acceptable. The sensitivity analysis should demonstrate the closeness to the hurdle rate which is the rate at which the investment gives unacceptable returns to the developer and could cause him to abandon the project.

Several factors can cause uncertainty in the financial input parameters. For example, the cost of drilling production wells to reach the target plant capacity is always uncertain due to the uncertainty associated with drilling success of geothermal wells. Schedules are always uncertain and therefore there is always a possibility that delays can cause financial parameters to deteriorate. Revenue can be lower than planned if target capacity is not achieved during the production drilling or if reservoir decline is faster than expected, calling for more frequent drilling of make-up wells than planned.

The sensitivity analysis should present graphs showing how the financial output parameters such as NPV and IRR, vary as estimated variables such as CAPEX, OPEX, revenue, time delay in project execution, vary within reasonable intervals. These reasonable intervals should be obtained from relevant chapters where the variables are estimated.

The sensitivity analysis can also include analysis of scenarios of project development that are deemed likely and can affect the financial outcome. This could for example include options for financial structuring of the project.

If probabilistic distribution of estimated variables is given distinct from an equal distribution on an interval, methods based on probabilistic sampling such as Monte Carlo simulation can be used to simulate the probability distributions of output variables. To indicate certainties, percentiles such as P90 and P50 should be used.

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APPENDIX A: GEOTHERMAL PROJECT RISKS¹⁸

Many of the risks of geothermal development are essentially the same as in other grid-connected power generation projects: completion or delay risk, off-taker risk, market demand or price risk, operational risk, social, environmental, political and regulatory risk. However, there are additional risks specific to geothermal energy development. The test drilling phase is often considered to be the riskiest. The highest risk is associated with the test drilling as it is capital intensive, while still fraught with high uncertainty about the generation capacity of the reservoir. Before the test drilling phase, significant investment in surface exploration is required to know whether the exploitation of the geothermal resource may be economically viable.

As explained in Section **Error! Reference source not found.**, when the project reaches Financial closure, the Field development phase has not concluded. Geological exploration risk is still present in the project that involves the risk of drilling the remaining production wells and reinjection wells to meet the planned capacity of the power plant.

One of the main purposes of a feasibility study report is to allow the financing entity to assess project risk. For a financing entity the primary concern is the probability that the developer can pay back the loan. The developer is likely to pay back the loan if the project will not come up against obstacles that can prevent project progress (showstoppers) and if the financial outcome of the project will remain acceptable to the developer. Other risk factors are of importance as well. For example, if social and environmental risks are not well managed in the project, the financing entity can be exposed to serious reputation risk.

Risk handling. A feasibility study report should disclose the main risks and in which manner they will be handled. The typical approaches to handling risk are:

- Avoid risk by selecting approaches that circumvent potential problems. This can include analysis of alternative approaches. As an example, the risk of a landslide affecting the plant can be avoided by moving the plant to a site where the risk of landslides is negligible.
- Control/mitigate risk. Control risk by reducing likelihood. Mitigation occurs when the event cannot be avoided, and the impact is offset through a set of additional measures/actions resulting in beneficial effects. The likelihood of cost overruns in plant construction can be reduced by proceeding further with the engineering design as the cost estimates accuracy depends on the maturity of the engineering design.
- Transfer risk to a third party. Risk transfer can be achieved in several ways. Contract agreements such as Engineering, Procurement and Construction (EPC) contracts for the erection of the power plant and the Power Purchase Agreement with an Off-taker, transfer construction risk in the first case and the market risk in the second. Financial instruments can include risk transfer such as political risk guarantee from regional financial institutions. Private finance institutions offer instruments such as convertible loans and bonds as well as derivatives to hedge financial exposure to specific risks such as currency changes. Finally, risk can be transferred to insurance companies through insurance contracts such as for Construction All Risk (CAR).
- Accept risk but include an appropriate budget for the possible cost overruns that it can induce. The risk of cost increases associated with failed wells cannot be avoided when drilling the production wells to acquire steam for the full plant capacity. It is therefore prudent to include and accept cost for failed wells in the budget for the production well drilling.

Risk and probability. Risks are often presented as a probability. A risk probability is the likelihood of occurrence. A common way to present risk probabilities in a quantitative way is with percentiles. The implicit assumption is then that the risk variable has a probability density distribution. The percentile of the distribution is a value P_α such that the probability of getting value smaller than or equal to P_α is $\alpha/100$. Typical values used in a feasibility study report are P_{10} , P_{50} , P_{90} , P_{95} and P_{99} . As an example, consider a variable with a probability distribution shown **Error! Reference source not found.** P_{10} , P_{50} and P_{90} equal 7,5 MW, 10 MW and 12.5 MW respectively. The relation between percentiles and the probability distribution function is that P_α is the value that area under the probability distribution function is α . In the figure below, the grey area is 0.1 of the total area under the probability density function. It defines the value of $P_{10} = 7,5$. Percentiles are often given for reservoir capacity. If the P_{10} of proven generating capacity of a reservoir is 50 MW, there is 90% probability that the generation capacity of the reservoir is above 50 MW. Percentiles are often the results of quantitative analysis using Monte Carlo methods where repeated random sampling is used to create distributions of calculated variables based on probabilistic distributions of input variables.

¹⁸ Extract from (ESMAP, 2012)

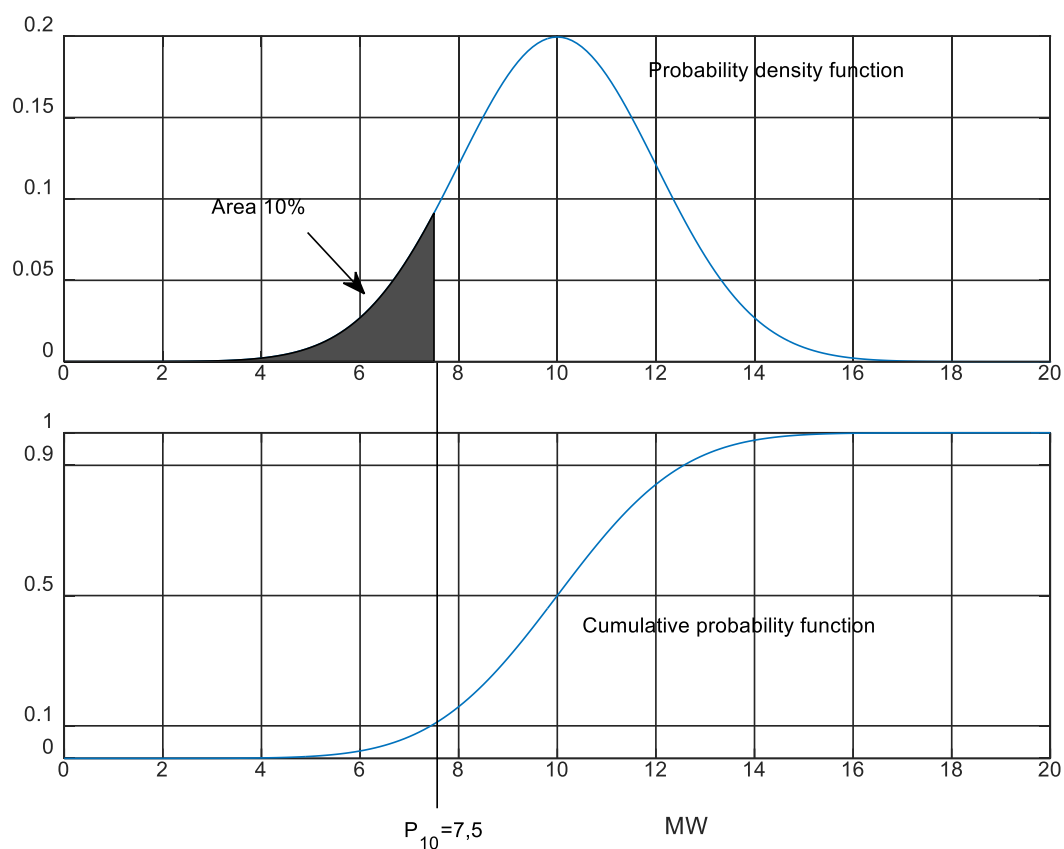


Figure 2. Percentiles, probability density functions and cumulative distribution functions.

Risk identification and risk classification. An integral part of risk management is risk identification and risk classification. To assess risk exposure, risks are often classified according to impact (changes in cost, schedule, revenue or other) and probability of occurrence. In **Error! Reference source not found.** typical geothermal project risks and risk categories are listed. The list is not meant to be exhaustive but to give a good overview of the risks present in a typical geothermal project. Note that the division in categories is not always crisp.

Table 1. Risk categories.

Risk category	Description	Example of risk handling	Related risks
Market risk	The market risk is the risk that the revenue of the project will not be as expected, not due to lower production but because the developer does not get paid for the production as originally planned.	Transfer risk to an off-taker by signing a Power Purchase Agreement (PPA). The market risk is then converted to off-taker default risk.	• Off-taker credit risk; • Price risk;
Geothermal resource risk	The geothermal resource risk at the time when the feasibility study report is written involves firstly the risk that the production drilling campaign fails to reach the required capacity, or it does so with cost overruns. It also involves the risk of decline in the resource due to exploitation of the resource that cannot be maintained for time-period planned. In this case the resource is not as productive as originally considered and the reservoir cannot sustain production to the power plant to produce according to planned capacity.	Reduce the likelihood of occurrence by performing further exploration of the resource using experienced specialist consultants. Transfer the risk through risk mitigation facilities if available. Develop the resource in phases with partial utilization/generation during the first phase and then stepwise increase in utilization. This can lead to a better understanding of the geothermal system, and a more accurate capacity estimate, before further exploitation is decided.	• Exploration drilling risk • Reservoir capacity risk • Reservoir decline risk • Reservoir sustainability risk
Location and site risks	Risk associated with the location such as natural hazards (earthquakes, hurricanes and volcanos). Risks associated with the site such as landslides and floods. Risks connected to the location such as security risks.	Select site to avoid natural hazards. Design infrastructure to withstand natural hazards.	• Natural hazard risk • Security risk
Technical risk	Risk associated with technical problems, be it during drilling, plant construction or plant operation. This can include quality problems, abandonment and non-completion. The impact can be increased cost, delays or revenue loss due to lower generation of energy.	The risk can be mitigated by investing further in the engineering of the project. The risk can be transferred to equipment suppliers and EPC companies. Contracts with these companies can include guarantees and penalties for delays.	• Construction risk; • Technical drilling risk;
Social and environmental risk	Risk of environmental damage caused by the geothermal power plant including any liability following such damage. Risk of delays and even project cancellation due to adverse social impact of power plant.	Carry out investigations according to internationally available guidelines regarding environmental and social impact assessment.	

Project execution risk	Risk due to delays in project execution. Risks due to management problems. Risks due to poor planning and inadequate budget not considering cost uncertainties. Risk due to difficulties in the procurement process.	Follow scheduling classification systems. Increase efforts in project planning. Follow procurement plans. Advanced engineering.	• Company risk • Procurement risk;
Financial risk	Risk of cost increase. Risk of delays, Risk of revenue loss, Risk of changes in financing conditions such as interest rate change or currency changes.	Financial planning should be based on proper financial analysis, including sensitivity analysis.	• Credit risk
Legal risk.	Risk related to the business transactions and contractual relationships in the project.	Mitigate the risk by engaging experienced legal counsel.	• Contract risk • Credit risk
Regulatory risk	Risks related to regulatory authorities whose decisions can impact the project either in the development or operation phase.	Contract expert consultant with knowledge of regulation environment.	
Political risk	Risk of project termination or delay due to political instability causing for example civil unrest and labor strikes.	Mitigate with social outreach programs. Political risk insurance.	
Operation and maintenance risk	Risks of unscheduled generation outages due to equipment failure or lack of resources for maintenance.	Assign adequate funding during operation phase.	

APPENDIX B: RESOURCE ASSESSMENT

The energy production capacity of hydrothermal systems is predominantly controlled by reservoir pressure decline caused by hot water/steam production, which is in turn determined by the size of a geothermal reservoir, its permeability, reservoir storage capacity, fluid recharge and geological structure. More generally the capacity of geothermal systems is also controlled by their energy content, dictated by their size and temperature conditions (enthalpy if two-phase). Thorough understanding of the nature and properties of geothermal resources, via comprehensive interdisciplinary research, as well as reliable and accurate assessment of their production capacity, through modelling, are an absolute prerequisite for successful long-term utilization of geothermal resources.

Modelling plays a key role in understanding the nature of geothermal systems and is the most powerful tool for geothermal resource assessment, or for estimating their production capacity, which is mainly based on predicting the response of the systems to future production, see (Axelsson, 2016). Models are also an indispensable part of geothermal resource management during utilization.

The volumetric method is the simplest modelling and assessment method used in the geothermal industry and is classified as static modelling. The other main techniques used for geothermal reservoir modelling and resource assessment involve different methods of dynamic modelling, including simple analytical modelling, lumped parameter modelling or detailed numerical modelling. The volumetric method using Monte Carlo calculations, supported by testing of drilled wells, is typically how resources are assessed in feasibility studies for greenfield systems, while in the case of expansion projects dynamic numerical models can be applied, if data coverage is sufficient.

The volumetric method is the main static modelling method, as already stated. It is presented and discussed in detail by (Sarmiento, Zosimo F. et al., 2013). It is often used for first stage assessment, when data are limited, and was more commonly used in the past, but is still the main assessment method in some countries. It is increasingly being used, however, through application of the Monte Carlo method, which enables the incorporation of overall uncertainty in the results. The main drawback of the volumetric method is the fact that the dynamic response of a reservoir to production is not considered, such as the pressure response and the effect of fluid recharge. Reservoirs with the same heat content may have different permeabilities and recharge and, hence, very different production potentials.

The volumetric method is based on estimating the total heat stored in a volume of rock (referred to some base temperature), both thermal energy in rock matrix and in water/steam in pores. In the volumetric method the likely surface area and thickness of a resource are initially estimated from geophysical and geological data, and later from well-data as well. Consequently, likely temperature conditions are assumed based on chemical studies and well temperature data, if available. Based on these, estimates of reservoir porosity and thermal properties of water and rock involved, the total energy content is estimated. The reservoir temperature can either be assumed to be approximately constant, to be variable between different reservoir parts or to be a certain fraction of the boiling point curve at prevailing pressure conditions, in the calculations. The reference temperature used is the base temperature of the energy production process involved (space heating, electricity generation, etc.).

Only a relatively small fraction of the total energy in a system can be expected to be extracted, or recovered, during a several decade long utilization period. This fraction is estimated by applying two factors. First so-called surface accessibility (A), which describes what proportion of the reservoir volume can be accessed through drilling from the surface. Then the recovery factor (R), which indicates how much of the accessible energy may be technically recovered. The recovery factor is the parameter in the volumetric method, which is most difficult to estimate. The results of the volumetric assessment are also highly dependent on the factor. It depends on the nature of the system; permeability, porosity, significance of fractures, recharge, as well as on the mode of production, i.e. whether reinjection is applied. It is also to some extent dependent on utilization time. In (Williams, 2007) a good review of the estimation of the recovery factor, which is often assumed to be in the range of 0.05–0.25, is provided. In recent years researchers have become more conservative in selecting the recovery factor than in the past, based on experience from long-term utilization of numerous geothermal systems worldwide.

To estimate electrical generation capacity (total energy or power potential) on basis of the recoverable energy an appropriate conversion-efficiency is used. It should incorporate the conversion of thermal energy into mechanical energy and consequently that of mechanical energy into electrical energy. The efficiency depends on resource temperature, the generation process used (conventional steam turbine, binary fluid generation, etc.) and the reference temperature.

The volumetric method can be applied to individual geothermal reservoirs, whole geothermal systems or on a regional scale, i.e. for a whole country. For individual systems the Monte Carlo method is commonly applied. It involves assigning probability distributions to the different parameters of the equations above and estimating the system potential with probability.

It must be emphasized that the volumetric method isn't suitable for the estimation of the long-term (sustainable) production capacity of geothermal systems. This is because of its limitations mentioned above, mainly the fact that it neglects the dynamic response of geothermal systems during utilization. Thus, the results of a volumetric assessment should only be considered indicative. It's also important to put emphasis on the lower limit of the Monte Carlo outcome, often referred to as the P95 or P90 value, rather than the average outcome or upper limit.

As the volumetric method isn't sufficient to estimate the ultimate capacity of a geothermal resource the results should be combined with the cumulative capacity of wells already drilled to plan the first development step. Detailed numerical modelling, performed once relevant data become available, will provide a much more accurate capacity estimate.