Valuing Research and Development Projects in Energy Markets

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1 Characteristics of Research and Development Projects

In this chapter, we highlight the importance of appropriately valuating research and development investments. We analyze the most important characteristics of projects in research and development. Projects in research and development are usually highly uncertain. They have a high degree of managerial flexibility, but investment expenditures are less reversible than e.g. capital expenditures on property, plants or equipment. We will accordingly analyze the typical types of uncertainty in research and development projects and suggest different systematizations of types and sources of uncertainty. Further, we highlight the importance of flexibility in such processes. We close the chapter by examining different types of flexibility, such as abandoning the project after certain important steps when new information emerges.

1.1 The Importance of Research and Development Projects

The development of new products or production technologies is of crucial importance for companies. Research and development activities ensure the competitiveness of a company and thereby play a vital strategic role in the company's success. Particularly in fast developing industries, a large portion of sales are generated by relatively new products. Being first to put an innovative product on the market is one of the most successful sources of competitive advantage. However, corporate innovation and activities in research and development consume huge amounts of resources. They are related to high capital spending. Since companies have only

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limited capital resources, a reliable valuation of research and development projects is of utmost importance for all companies. The main objective of this allocation process of limited resources to the development projects is to increase the firm's entire value. Appropriate valuation tools ensure optimal investment decisions in research and development projects, and are thereby the key for an efficient allocation of the resources that a company spends on the development of innovative products. Additionally, due to the frequently long development phases and the huge amounts of necessary resources, well-developed controlling and project management is the backbone of a successful research and development process and the company's resulting success.

Projects in research and development have special characteristics that make their valuation and controlling exceptionally difficult. In particular, standard valuation tools, such as net present value techniques, fail to capture all aspects of such projects. The inherent characteristics of development processes are several substantial uncertainties. These can, for example, include the level of capital expenditure that is necessary for the whole development process, the technological success of the development efforts, or the market success of the innovative product. An important driver of uncertainty is the time lag between the development decision and the marketability of the developed products. Depending on the type of product development activity, this time lag can be quite long. Uncertain future price developments of necessary raw materials or of potential substitutes for the developed product are important drivers of project value. These uncertainties present a special challenge for the valuation of research and development projects.

Another characteristic of development projects that a valuation tool must be able to capture is the set of potential actions and flexibility that management have during the development process. While there is a high degree of ex-ante uncertainty, management can react to emerging information during the development process. There is a large range of examples of such flexibilities and potential actions. For example, a substantial change in the structure of material costs can make an alternative technical solution more attractive. Further, the developed product can be more attractive for other markets than the one it had been planned for originally. Farthest reaching, technological difficulties or market changes can make it necessary to stop the development at certain milestones. Obviously, a valuation tool must consider such flexibilities.

The relevance of uncertainty and flexibility is increased by the usually long time lag between the initial investment expenditure and the first cash inflows from the project. Moreover, even the actual development period is uncertain and can be influenced by higher or lower investment expenditures. A further characteristic of research and development projects is the dynamic during the development phase. Effective accomplishment of milestones and monitoring the development of relevant risk factors during the development phase is key for the success of the project (see Granig 2007, p. 52).

1.2 Identification and Classification of Different Sources of Risk in Development Processes

As pointed out in the previous section, incorporating the uncertainties and risks of a research and development project in its valuation is crucial. Decisions about the realization of research and development projects have to consider many different sources and types of risk. For example, it may not be clear how the market for a new product will develop, how competitors will react to the company's decisions, what government and regulating agencies do, or what volume of resources is necessary to successfully develop the new product. Due to the usually high and typically irreversible investment expenditures, a failure to include a proper assessment of such risks in the decision-making process can become a substantial threat to the whole company. Thereby, it is important to identify the relevant risks, to assess these risks and finally, to manage and mitigate the relevant risks throughout the whole project.

When valuating investment projects, a company typically compares the expenditures that are necessary for the project with the cash inflows resulting from the realized project. However, neither the expenditures nor the actual cash inflows are usually known before the project is realized. Therefore, in the first place, one can distinguish risks that affect the expenditures, or cash outflows, and risks that affect the cash inflows. An exemplary systematization of types of uncertainty is given in the Fig. 1 below.

There can be different sources of risk in cash inflows. When the company has to make the investment decision for a potential development process it usually knows neither the quantities of the developed product that will be sold nor the prices that can be obtained for the product on the market. The price-demand curve can provide an idea of the interdependency of price and the quantity sold. However, even the course of the price-demand function will usually be uncertain at the early stage when the investment decision has to be made. For example, the price-demand curve for technical investment goods will depend on the development of the market for

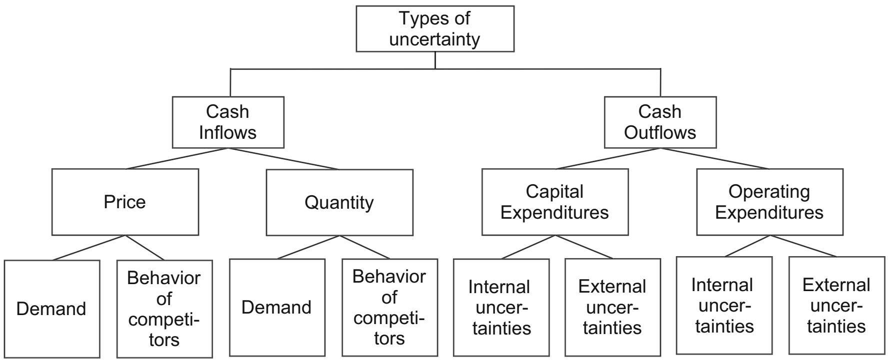

Fig. 1 Systematization of types of uncertainties in research and development projects (Source: Friedl 2001)

the goods that are produced therewith. Other uncertain determinants of the demand for the products can be the clients' preferences as well as the development of the whole economy (see Friedl 2001, p. 27). It is also uncertain how competitors will react to the development of new products. The behavior of the innovator's competitors can influence both the quantity sold and the price of the newly developed product.

Regarding expenditures for the project, one can distinguish capital expenditures and operating expenditures. Uncertainties in both types of expenditures can stem from internal and external sources. External sources could be costs of inputs necessary for the production of the newly developed product. Internal uncertainty in the operating expenditures can include the uncertainty about the quantity of production factors that are necessary to produce the product. But even capital investments can be uncertain. In particular, it is often unclear how long the development process of a certain product will last, and which resources the development process needs.

For an analysis of the risk factors in the course of the valuation, it can be helpful to distinguish different types of risk. In research and development projects there are typically market-related risks. They contain all kinds of uncertainty that relates to the question of what the company can earn with the product during its life cycle. Further, there are different technological risks. This means that certain properties of the planned product cannot be realized or that its development becomes more complex and time-consuming than expected. Besides the market-related and technological risks in research and development projects there can be regulatory risks. During the long development periods the regulatory environment can change and new regulations can influence the marketability and success of the product.

For the valuation of uncertainty, it is important to establish whether a market price for the uncertainty exists or not (see Friedl 2001). By definition, in a complete capital market, a market price for each uncertainty exists. If such a market exists for a particular risk, the risk is referred to as a market risk. An obvious example of a market risk is the purchase of a company's stock. The future cash inflows from the company are uncertain, but the current stock price reflects these risks. However, in reality it is hardly conceivable that each uncertainty can be valued by market prices. For example, consider a company that develops a completely new product. There is substantial uncertainty as to whether the development will fail or can be successfully completed. Moreover, the time to completion is uncertain. These kinds of technological risks are typically private risks for which no market exists (see Smith and Nau 1995, p. 807 or Amram and Kulatilaka 1999, p. 56). Usually there is no information from the market such as a stock price that can be used to assess this risk.

The existence of market prices enables a quantitative provision for market risks in valuations of research and development projects. Consider for example the need for a certain amount of a raw material for the production of the developed product. For example, the price of a call option for the respective raw material that can be derived by arbitrage arguments from the price development of the underlying raw material gives a market price incorporating the risk of a significant change in the price for the respective raw material. In contrast, it is more difficult to take private risks into account quantitatively. Typically, the evaluation of private risks, such as technological risks, depends on the estimations of the decision-makers. Estimations of experts or experiences gained from earlier projects can help to evaluate probabilities for certain private risks, such as the technical feasibility of a planned product. Another way to estimate private risks is to rely on historical information. For example, a company can analyze how often the development of new products in a certain branch had been successful in the past. The share of successful development projects in the past may be a useful approximation for the probability of success of the current project.

To sum up, risk and uncertainty are unavoidable characteristics of innovative research and development projects. A company should carefully identify all relevant risks and consider them in the investment decision. Later in the development process, consistent risk management can reduce the risks or the negative effects of a potential occurrence of a risk.

1.3 Multiple Stages and Flexibility in Research and Development Projects

In the previous section we identified uncertainty as a major characteristic of investments in research and development projects. While cash inflows as well as cash outflows from such projects are usually uncertain, the company often has the flexibility to react to events and information appearing during the development process. In particular, the assumption of a single initial investment that is often made in classical capital budgeting and investment theory is overly simple for this kind of investment projects (see Friedl 2001, p. 19). Instead of a single initial investment, capital expenditures actually occur in multiple stages during the investment period. This allows for an obvious kind of flexibility: For each investment stage the company can usually decide whether it wants to continue the project and spend further money or to abandon the project.

In addition to the drastic measure of abandoning the whole project, the company often has other flexibilities with which to react to new information emerging during the development process. For instance, it might be valuable to delay the further development until new information has been gathered. A particular change in the regulatory environment might be expected which would influence the economical profitability of the developed product. In such a situation, a company can defer the further capital expenditures until clarity regarding the legal regulations has been achieved.

We have already discussed the fact that it is not or cannot necessarily be specified in advance on which exact market or market segment a developed product will be offered. During the development process, it can turn out that an innovative technology can be used for different new products, or have a higher economic impact in another product or market than originally planned. Greater technological success or changes in the target market, such as an expected increase in customer demand can make an expansion of the project or an acceleration of the development advisable. These possible actions and alternative decisions facing a company during the development and investment process are often referred to as real options. The different kinds of real options and potential approaches to value the advantage that a company achieves from the flexibilities will be analyzed more systematically in Sect. 2.3.

Besides the described potential reactions concerning market and investment decisions, there are usually many technological details that are not, or not precisely specified when a project is first considered. So far we have discussed business, investment and market decisions that have to be made and allow for a certain degree of flexibility during the development phase. Besides these, there are technological degrees of freedom that allow for some flexibility depending on new information emerging during the development process. Most importantly, such information can affect development success. If it turns out that a certain technological specification is not obtainable by the planned technical realization of the product, it may be necessary to find new possibilities for the technical realization or to change the intended technological specification of the product. Furthermore, the company may recognize previously unconsidered future needs of the market that makes it worth changing the technological specification of the developed product. When making the initial investment decision, the company must be aware of the economic and technological flexibilities and their interactions in order to make an optimal investment decision.

The degree of reversibility of investment expenditures is another important determinant of the value of research and development projects. Usually investments in property, plant and equipment have a relatively high degree of reversibility, because the respective goods are marketable and can be sold by the investing company. The more specific an investment is for a certain industry or even company the more likely it is to be irreversible (see Dixit and Pindyck 1994, p. 8). Investments in research and development in particular are often not reversible. The most obvious example is the investment expenditure in a research and development project that turns out to be unsuccessful. In addition, unfinished development activities are of course not marketable for the company. Thus, investments in a development process that has already been carried out are hard to reverse. On the other hand, the multiple stages structure of such investments projects allows for a postponement of expenditures. It is not necessary to make the full expenditures at the beginning of the development process. Therefore, irreversibility can be reduced by staggering investments over several phases.

2 Tools for Valuing and Managing Investment Projects in Research and Development

In the previous sections we identified and explained the most important characteristics of investment projects in research and development. Frequently, the expenditures in research and development projects are to a high degree irreversible. Moreover, project expenditures and project revenues are risky. Furthermore, the sequential nature of investment in innovation and development projects allows management diverse economic and technological flexibilities during the development process. This section describes the shortcomings of prominent tools for capital budgeting decisions in research and development. Moreover, we present modern techniques for such valuation tasks, and in particular propose real option approaches as a technique for improving research and development valuations.

2.1 Shortcomings of Classical Valuation Tools for Projects in Research and Development

One of the most important tools for capital budgeting is net present value analysis. The net present value offsets current and future expenditures against forecasted future cash inflows generated by the respective project. The net present value analysis incorporates the project risk in a very simple way. Future cash flows are discounted using a project-specific discount rate that accounts for the riskiness of the project. The higher the risk is, the higher is the discount rate, and the lower is the present value of future cash flows. Indeed, the net present value approach is superior to alternative valuation measures under the assumption of a single stage investment without any flexibility (see Trigeorgis 1996, p. 24). However, this approach has several shortcomings when applied to a project in an uncertain environment with managerial flexibility after the initial investment decision.

Firstly and most importantly, this is because the net present value analysis is a static tool. Only one major project decision based on the information available at project outset is included in the analysis. Thus, the net present value analysis cannot incorporate future managerial flexibility during the course of the project. Hence, several authors argue that net present value approaches might lead to a systematic undervaluation of innovative research and development projects with a high degree of managerial flexibility during the development phase. Suppose, for example, the simple option of abandoning a development project at a certain milestone. The company would exercise this option and abandon the project if the recalculated net present value of the project at this milestone were negative. As a consequence, future cash inflows and cash outflows after the abandonment decision would be zero or at least significantly reduced. Since the net present value analysis cannot integrate this flexibility, it is not clear whether a project with a negative net present value is really a bad one.

Secondly, it is very difficult to capture different types of risk in net present value approaches. Usually expected future cash flows are discounted with a risk-adjusted discount rate. Market risks are comparably easy to capture in a risk-adjusted discount rate. For example, the Capital Asset Pricing Model (CAPM) offers a method for calculating a risk-adjusted discount rate by taking into account the correlation of a certain asset with the market portfolio. The correlation of a risky asset with the market portfolio is the main factor for the risk-adjusted discount rate in the Capital Asset Pricing Model. Hence, a condition for this approach is that a marketable security for the respective risk exists. Otherwise the Capital Asset Pricing Model would not be able to capture the respective risks because the correlation with the market portfolio cannot be calculated.

Suppose, for example, the technological risk that the development of an innovative product will fail. If the development fails, none of the forecasted cash inflows from the project can be realized. However, there is no marketable security that reflects this risk and it is hard to appropriately adjust the discount rate for it. In general, market risks are easier to consider by risk-adjusted discount rates whereas technological or political risks are hard to capture by discount rates. To sum up, the net present value approach is a tool which is superior to other valuation tools in an environment with no managerial flexibility after the initial investment decision, and the presence of mainly market risks that can easily be accounted for by risk-adjusted discount rates.

Alternative approaches attempt to better incorporate uncertainties and the influence of managerial flexibility on the value of investment projects. A frequently used tool is sensitivity analysis. This tool analyzes the influence of a change in a primary variable on the value of the project (Trigeorgis 1996, p. 52). This approach helps to identify the variables that can lead to a substantial threat to the success of the project. An example of a main value driver of a development project is the price level of the innovative product. A sensitivity analysis shows how the value of the project changes when the assumptions for the price level change. An important factor for the decision may be the critical price level that is necessary to achieve in order to make the project profitable. The sensitivity analysis helps to better understand the influence of certain primary variables on the project's value. However, it still has considerable shortcomings. For example, it fails to capture interdependencies between different uncertain variables that commonly influence the value of the project. Further, the scenario analysis is hardly able to capture other qualitative risk factors such as the development's success. Most important, it is still a static tool, which is not able to take managerial flexibility during the development process into account.

The lack of recognized interdependencies and technological risks can be addressed by scenario analysis. In contrast to sensitivity analysis, which analyzes the isolated influence of a single primary variable, scenario analysis incorporates uncertainty by comparing the project's value in different scenarios. These scenarios can differ in all primary variables and assumptions. However, each scenario still considers a fixed investment plan with no managerial flexibility. Scenario analysis does not allow for an explicit consideration of managerial flexibility during the investment period (see Amram and Kulatilaka 1999, p. 39). Scenario analysis can be extended by a simulation analysis. This allows analyses of a very large number of possible scenarios for the uncertain variables. However, this does not solve the problem of allowing for managerial flexibility and decision opportunities after the initial investment decision. In the next section, we discuss two tools that can explicitly take into account these flexibilities.

2.2 Capturing Risk and Flexibility with Decision Tree Analysis

An alternative tool for capital budgeting in research and development projects is decision tree analysis. It makes a first step towards fully recognizing managerial flexibility in research and development projects. This approach addresses the two main shortcomings of net present value analysis. Firstly, in a decision tree analysis it is possible to capture and differentiate different types of risk. Secondly, one can explicitly take managerial flexibility into account in a decision tree analysis. It allows inclusion of potential subsequent decisions and their effects on the project's value (see Trigeorgis 1996, p. 57).

In order to use decision tree analysis, the decision situation must be carefully modeled. A model of the decision situation includes three components: decision nodes, event nodes, and terminal nodes. A decision tree always starts with a decision node, which represents the first decision. For example, the initial decision of whether or not to invest in a new product development project is one node with two possible decisions—investing or not investing. Subsequent decisions, such as abandoning the project, are also modeled as decision nodes. Uncertainty is modeled using event nodes. They represent events that the decision-maker cannot control. Whenever uncertainty resolves, you need to model this with an event node. For example, whether a certain technological specification can be achieved or not is an event node with two possible outcomes. Decision nodes are usually preceded by event nodes because uncertainty makes the option to decide valuable. Finally, the payoff is modeled at the end of each branch in the decision tree. This payoff is modeled as a terminal node. For example, a terminal node can represent the value of a successful product development, taking into account all future revenues and operating expenses.

In a decision tree, the value of the project and the optimal actions contingent on the states of nature are determined simultaneously and backwards. For each decision node, the value-maximizing action is determined. There are two basic ways to value uncertain future cash flows at an event node of a decision tree. The first possibility values uncertain future cash flows with their certainty equivalents and discounts them at the risk-free discount rate. The second possibility is based on the expected value of the uncertain future cash flows. The expected value is then discounted with a risk-adjusted discount rate. Both concepts have certain difficulties. To calculate the certainty equivalent, it is necessary to know the decision-maker's utility function. Instead the second approach requires a calculation of the risk-adjusted discount rate that in turn depends on the chosen strategy.

Thus, an important ingredient for obtaining the optimal decision is a detailed modelling of the decision situation with all future decisions and uncertainties. The main advantage is that decision tree analysis allows consideration of different types of risks as well as managerial flexibility explicitly. However, it remains important to evaluate probabilities for the events at event nodes. This can be challenging, especially for private risks such as technological risks. Expert interviews and experiences from past development projects can help to assess the chances and risks that a development will successfully lead to a new, innovative product. An alternative to explicitly considering managerial flexibility in uncertain decision processes that utilizes market expectations about certain risk factors is the real option approach, which will be discussed in the next section.

2.3 The Real Option Method as a Tool for Improving the Valuation of Research and Development Projects

The previous sections showed that innovative projects in research and development usually provide diverse managerial flexibility while the project is conducted. Management can choose from several potential actions to react to emerging information. These flexibilities can be viewed as real options for management. While classical valuation tools assume that there is no managerial flexibility after the initial investment decision has been made, research and development projects typically consist of a set of real options that can be exercised during the lifetime of the project. The managerial flexibilities are options that can be exercised, but they need not necessarily be exercised. For example, only if the success of the development seems to be threatened, or new information shows that the product cannot be successful in the market, the company would exercise the option of abandoning the project and development efforts. These characteristics suggest the application of option valuation techniques to value managerial flexibility in innovation processes.

Financial option valuation is a well-developed tool, heavily used in the finance sector. A financial option is a right usually without an associated obligation to buy or sell a specified asset for a predefined price (see Trigeorgis 1996, p. 69). Options with the right to buy a certain asset are called call options whereas the right to sell a certain asset is called a put option. The specified price to buy the asset is called the exercise or strike price. Options are traded on all imaginable underlying assets such as common stocks, stock indexes, commodities, foreign currencies, corporate liabilities and so on. In 1973, Fischer Black and Myron Scholes, and later Robert Merton in a generalized version, published a simple method of valuing derivatives such as financial options (see Black and Scholes 1973; Merton 1973). Merton and Scholes were awarded the Nobel Prize in Economics in 1997 for their findings on option pricing theory. The basic idea behind the theory of option valuation is that the payout structure of an option in any state of nature is exactly replicable by a certain portfolio of assets. Then it is easy to calculate the value of the option by simple arbitrage arguments. The replicating portfolio must have the same value as the option order to avoid risk-free arbitrage profits because it provides the same future returns.

To apply financial option valuation techniques to valuing real options it is necessary that an underlying asset with a market price exists, which has the same risk structure as the option. This means that the market-valued asset must approximate the value of the project in each state of nature sufficiently exactly. For market risks in development projects, such assets exist per definition. For such risks, the application of valuation techniques for financial options can be a powerful instrument for valuing real options. For private risks such as technological risks, on the other hand, such assets do not exist. It is hardly imaginable that there might be an asset with a performance that mirrors the probability of the technological success of a product development process.

There is a wide range of possible managerial actions in research and development projects. Here the most important of the numerous real options that can occur in such projects are highlighted. The most drastic decision is to fully abandon the development project. The respective real option is called the option to abandon. It can become advisable to exercise the option to abandon if the probability of a successful development becomes uneconomically low. Another reason may be new market information or a development in the market that makes it unlikely that the new product will be successful. Though this is the most drastic managerial action, it is one of the most frequent occurring real options, which is also regularly exercised in practice. Prior to each stage of a multiple-stage investment project in research and development, it is possible—and due to the gradually resolving uncertainty—highly advisable to review the project and its continuation. This is a direct consequence of the multiple-stage structure of investment projects in research and development.

If it is not advisable to immediately and fully abandon the project, it can still be advisable to delay the investment project for a while. It may be worth exercising the option to delay if, for example, more information about market development is needed. A similar option is the option to defer. This option refers to the optimal point in time at which to start a research and development project. Not only can the decision if and when a project is contracted be made during the development phase but the scale and the intensity of development effort can be influenced. Management has the option to expand and the option to contract the corporate development effort for a certain project.

Real option analysis has helped to highlight the numerous types of managerial flexibility that appear in research and development projects as well as many other corporate multi-stage investment projects. It enables a smart and easy valuation on the assumption that the market is complete in the sense that every risk can be perfectly reproduced by marketable securities (see Smith and Nau 1995, p. 804). This assumption, however, is true only for market risks by definition. But if risks cannot be fully hedged by marketable securities, one can still use decision tree analysis to include private risks and managerial flexibility in the decision process. The relationship between decision tree analysis and the real option method has been extensively researched in academic literature (see Smith and Nau 1995, p. 804). Smith and Nau (1995) showed that on the assumption of complete and perfect markets, the decision tree analysis and the real option approach lead to equivalent results. Trigeorgis and Reuer (2016) provide an overview on real options theory in strategic management.

Usually a decision-maker will have to face private risks and market risks. Smith and Nau (1995) suggest an approach that combines the advantages of real option valuation and decision tree analysis. They therefore set up a combined decision and state tree. Each event node can represent either a private or a market risk. Hence, the first step is to clarify whether a certain risk is private to the innovating firm or whether it is a market risk. After setting up the decision tree, it will be resolved backwards from the terminal nodes of the tree. For each event node with a private risk the certainty equivalent for the node is calculated based on the utility function of the decision-maker and the assessed probabilities for the different states. The value for a chance node that refers to a market risk is calculated based on real option valuation techniques. Thus the hedging portfolio is calculated and the value of the respective portfolio is discounted by the risk-free discount rate. For each decision node the value-maximizing decision is chosen. It is still unclear how the utility functions can be determined. Smith and Nau suggest applying the assumption of risk-neutrality, at least for large publicly held companies because the owners should be broadly diversified and, hence, indifferent concerning the private risk of a single company (see Friedl 2003; Smith and Nau 1995, p. 808).

2.4 The Stage-Gate Process to Manage Flexibility in Research and Development Projects

Once the initial project and investment decision has been made, project structuring, management and controlling becomes crucial to ensuring the project's success. The main goal is a project management that enables a fast and friction free development process, risk avoidance and minimization, the monitoring of the progress that the project is making, and finally, the monitoring of the identified risk factors for the project. Managerial flexibility during the development process can only be utilized if the project plan allows the management to consider certain decision opportunities, and forces the systematic collection and exploitation of information that emerges during the development phase.

A helpful tool in managing innovation processes is the Stage-Gate Process proposed by Cooper (2002, 2008) and Granig (2007). The Stage-Gate Process is a systematic scheme for managing a research and development process. The important process steps (stages) are marked by pre-defined gates. Each gate is connected to an explicit abandonment or continuation decision. Only if the determined criteria are in favor of a project continuation, will it be continued and further resources allocated to the project. The method aims at shortened innovation processes, optimal resource allocation and risk limitation (see Granig 2007, p. 24).

Figure 2 shows an example of a stage structure for innovation processes (see Granig 2007, pp. 193; Cooper 2002): At the first stage the scope of the project is determined. Technological advantages of the project are analyzed and a rough

Fig. 2 Stages of an innovative process (Source: Own illustration based on Granig 2007, pp. 192)

market analysis is conducted. Following this, at the second stage, the business case is built. The product specifications are defined and a detailed market analysis is conducted. If the chances of economic success and the evaluation of the financial analyses at the second gate are positive, the third stage begins. Here the actual development of the innovative product takes place. Usually some of the ex-ante uncertainties regarding the technological feasibility and the market success of the product are revealed in this phase. At the following gate, the realization of the planned product and its specification is decided. Further, the economic data about a potential market success are reviewed for a later market launch. At the fourth stage, the product is tested and validated. The product should be brought to market maturity here.

Comprehensive testing is conducted to avoid failure costs later. The final gate prior to the market launch at the fifth stage focuses on the results from the testing and validation stage. If all criteria regarding the product, its specification, and the respective target market and financial analyses are fulfilled, the product is launched at this final stage. The stage-gate method underlines the multiple-stage character of research and development investments. Each gate offers the explicit chance to abandon the project if new information recommends the abandonment. Only the investment expenditures that are necessary to perform the next stage are approved at each gate. Based on our discussion on characteristics and valuation tools for research and development, in the subsequent section we will analyze Siemens' decision to develop its H-class Gas Turbine. We will also describe the management of the development process.

3 Case Study: Development of the H-Class Siemens Gas Turbine

In this chapter we describe and analyze the decision-making process at Siemens for the development of the H-class Gas Turbine. The chapter starts with an overview of energy markets. We especially focus on the role of gas-based electricity generation for the worldwide power supply. The chapter proceeds with an analysis of the market for gas turbines, the global players, clients, and market development. Section 3.2 shows the historic development of Siemens gas turbines. Section 3.3 analyzes the development decision regarding the Siemens H-class Gas Turbine. It starts with an analysis of the strategic reasons for the development of a new generation of gas turbines and the goals that Siemens pursued in the development of the H-class Gas Turbine. We describe the different forms of analysis Siemens did to substantiate the investment decision. We also review the arguments that lead to the decision in favor of the development project. The analysis proceeds by showing the significant risks and uncertainties that had to be faced by Siemens when the decision was made. We describe the project plan and multiple stage structure of the investment that had been chosen to handle these risks and to be able to react to new information during the development phase. Finally, we show how Siemens managed and controlled the actual development process and provide a prognosis on the market success of the H-class Gas Turbine.

3.1 Overview of Energy Markets: A Snapshot, Trends and the Importance of Natural Gas in Power Generation

Between 1991 and 2015 worldwide power generation almost doubled. In this period it increased from 12.106 TWh in 1991 to 23.208 TWh in 2015. In particular, emerging regions such as South America, Asia and the Middle East have seen a fast-rising power demand and there is still a steadily increasing and worldwide demand for reliable, flexible and cost-effective power generation (Source: IHS Energy 2016, Rivalry scenario). Scarcer resources and an increasing awareness of environmental pollution and climate change demand more efficient, flexible and sustainable power generation. The typical energy sources that are used for power generation are coal, natural gas, nuclear power, lignite, wind, water, and other regenerative energy sources. Figure 3 shows the worldwide distribution of energy sources for power generation in 1990 and 2015.

Since 1990, the share of natural gas in worldwide power generation has increased from 14.8% to 23.0%. In absolute numbers, this is an increase from 1756 TWh per year to 5488 TWh per year (Source: IHS Energy 2016, Rivalry

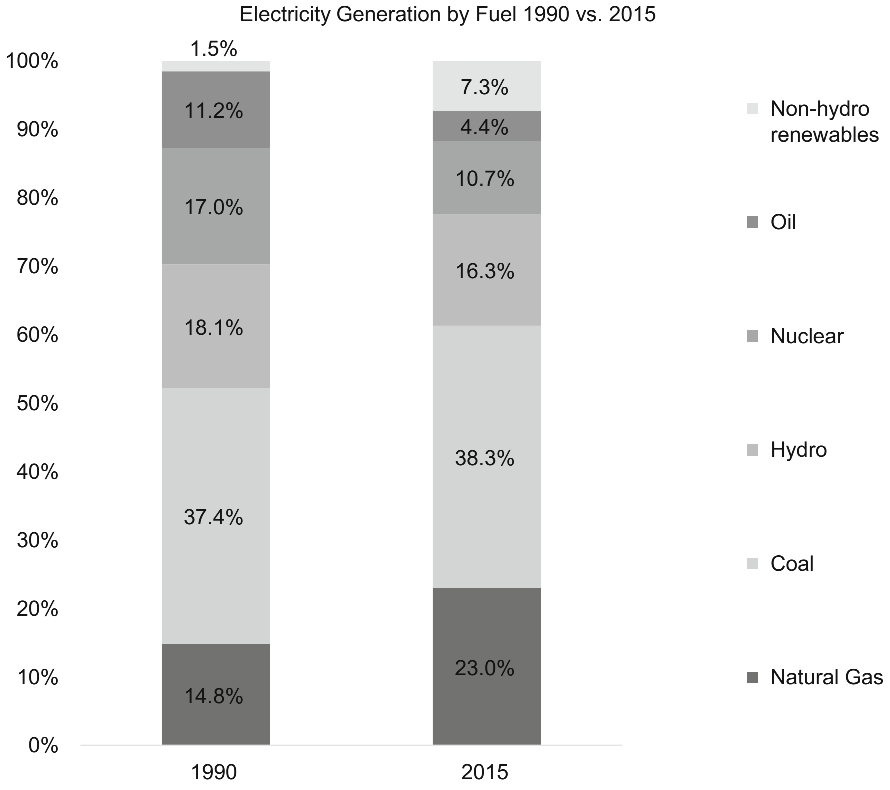

Fig. 3 Electricity generation by fuel, 1990 and 2015 (Source: IHS Energy 2016)

scenario). In Europe, this trend is even more significant: Since 1990 the share of natural gas in European power generation rose from 7% to about 17% in 2015 (Source: IHS Energy 2016, Rivalry scenario). The share of gas in electricity generation differs widely between countries even within Europe. The Netherlands, with the highest share in Europe, generates more than 50% from natural gas whereas Sweden generates almost no power from natural gas. Germany produces about 10% of its electric power from natural gases. Until 2030, the annual total of worldwide electricity generation is expected to rise to 34,400 TWh. This implies an annual growth rate of 2.5%. Further, the share of gas in total electricity generation is expected to increase to 24% of the total worldwide electricity generation. The largest rise is expected to be seen in the share of renewables electricity generation, from about 4% in 2011 to 17% in 2030.

The importance of combined cycle power plants is currently significantly increasing, but the reasons for this trend are manifold and vary for different global regions. In the United States in particular the price for natural gas has fallen sharply since hydraulic fracturing has offered a new, comparably cheap way to drill for natural gas. This price decrease makes it economically more attractive to obtain electricity from natural gas. In the medium run, new means of gas production will also lead to a certain extent to a decoupling of the gas price from the oil price that can make gas as an energy source for electricity generation even more viable. In countries with very low gas prices, combined cycle power plants can even contribute to base load capacity.

By contrast, for example, in Germany, base load coverage with natural gas is uneconomical due to the high gas prices in Central Europe. Whereas the average price in 2016 in the United States was USD2.5 per MMBtu, in Germany it was USD4.4. Thus, gas-based electricity generation is typically used for medium and peak load coverage in Germany. Short start-up times are vital for a power plant to be suited for coverage of peak loads. It is usually possible to rev up a gas-fired, open cycle plant within a few minutes. With a rising proportion of renewables generated power the importance of gas power stations might even increase. With a traditional, mainly fossil fuel electricity production mix, the main reason for unexpected need for additional capacity was occasional peaks in the power demand.

With a rising share of regenerative sources, a second source of unexpected need for additional capacity appears: It is very hard to predict whether the sun will shine or whether and with what speed the wind will blow at a certain time of a certain day. Thus, in a network relying to a high degree on energy from sunlight and wind it will be necessary to get quickly available power when energy from regenerative sources experiences unforeseen changes within a short time. Though combined cycle power plants can solve this problem, there is an inherent economic problem. If subsidized regenerative energies are available during a relatively large number of hours during the year, gas turbines run only during a relatively low number of hours, even though they have an important function in guaranteeing a reliable power supply. However, it can become inefficient for power suppliers to invest in combined cycle power plants if they rarely operate during the year. These trends also increase the pressure on OEMs of gas turbines to reduce the investment and operating expenses for power suppliers using gas turbines.

In the long run, extended transport capacities might lead to more trade of gas between different regions of the world and thereby less significant differences in prices. Thus, gas prices in different regions of the world might converge, leading to lower prices in Europe and the Far East. Trade is currently restricted by fully utilized transport capacities. To sum up, the worldwide power markets are expected to further increase, and due to several global trends make it likely that the share of gas in total power supply will also rise. In the subsequent section we take a closer look at the market for gas turbines.

3.2 Gas Turbines: History and Market Analysis

The H-class Siemens Gas Turbine is the latest generation of gas turbines developed by Siemens. Gas turbines are used in power plants to generate electricity from natural gas. Today the large, heavy duty gas turbines are usually installed in combined cycle power plants. In a combined cycle power plant, natural gas is used to drive a turbine generating electricity by a generator. The hot exhaust gas from the gas turbine is utilized to evaporate water for a downstream steam turbine. Using this combination, the highest efficiencies can be reached because unlike a pure gas power plant, the energy from the hot exhaust gas is not wasted. The launch of the H-class Siemens Gas Turbine development project dates back to October 2000. After a 5 year development phase, followed by 2 years manufacturing, and 1 year installation, the prototype of the gas turbine was first employed in a power plant in Irsching for validation purposes from 2008. In 2011, the extended combined cycle power plant in Irsching went into operation. The first commercially ordered turbine was inaugurated in 2013 in Florida. It is the first gas turbine with a combined cycle net efficiency of over 60%, which is an increase in efficiency of about 1.7% points compared to the predecessor, the Siemens F-class Gas Turbine. Besides the outstanding efficiency rate, a high degree of flexibility via short start up phases and high part load performance, high reliability, and reduced life cycle costs are the main characteristics of the new generation of gas turbines.

The Siemens H-Class Gas Turbine falls under the category of large gas turbines (LGT). LGT are gas turbines with power of more than 60 MW. The average unit price for large gas turbines is about EUR 20 million to EUR 50 million depending on the output sizes and the contract volume. That comprises the cost of the turbine, the generator, the process control technology and the side systems. There are currently four original equipment manufacturers (OEM) for large stationary gas turbines with a capacity of more than 60 MW: General Electric (USA), Siemens Energy (Germany), Mitsubishi Hitachi Power Systems (Japan) and Ansaldo (Italy). Alstom Power (France), another manufacturer of large gas turbines, was acquired by General Electric in 2015.

In 2012, Siemens had an overall market share by ordered capacity of 28% of the whole market for gas turbines. The market leader was General Electric with a market share of 43%. Mitsubishi Hitachi Power Systems was third with a market share of 18% and Alstom followed with 4%. The global market ordered a total capacity of 53,429 MW or 585 gas turbines including smaller and mid-range gas turbines. The ranking of the four market players has been stable over the last few years. Between 2007 and 2012 the market share of General Electric ranged between 40 and 48%, Siemens between 24 and 39%, Mitsubishi Hitachi Power Systems between 7 and 18% and Alstom between 2 and 11%. However, in some years Siemens could catch up with its main competitor General Electric. For example, in 2009, General Electric had a market share of 41%, compared to Siemens with a market share of 39%. Figure 4 shows the development of market shares between 2007 and 2012.

Following with the financial crisis, the gas turbine market has seen significant fluctuations in demand over recent years. Shortly before the crisis began in 2007 a total capacity of 82,294 MW was ordered. This rapidly fell to a low demand in 2009 when only 46,011 MW were ordered. Though the market recovered slightly, one could still observe large fluctuations in the following years with an ordered capacity of 74,675 MW in 2011, and, as stated above, again only 53,429 MW in 2012. Low gas prices and a higher demand for flexible power production offer good prospects of a positive market development for gas turbines. The research firm Forecast International estimates that the market volume for the next 10 years will be 12,000 gas turbines worth about EUR 168 billion. A market study by IHS Energy from 2016 forecasts a solid market growth for the global gas turbine market until 2030: globally new installations of gas fired power plants grow from 46 GW in 2015 to 71 GW in 2030 (Source: IHS Energy 2016, Rivalry scenario). Clients for large gas turbines are worldwide power plant operators. Countries with the largest

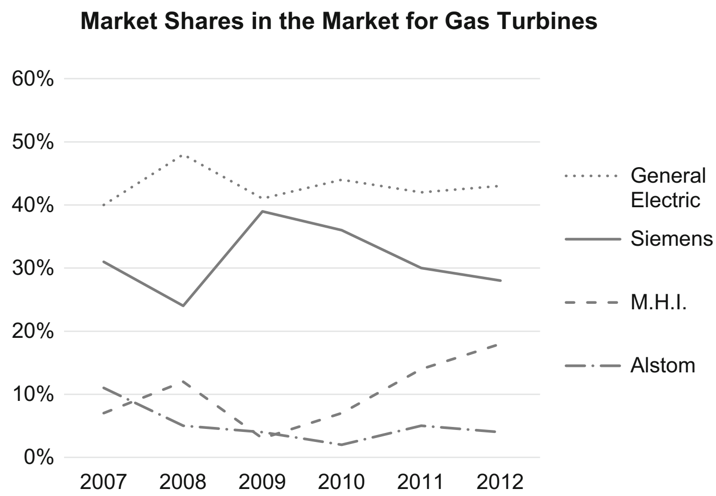

Fig. 4 Development of market shares measured in MW of delivered capacity (Source: McCoy Data)

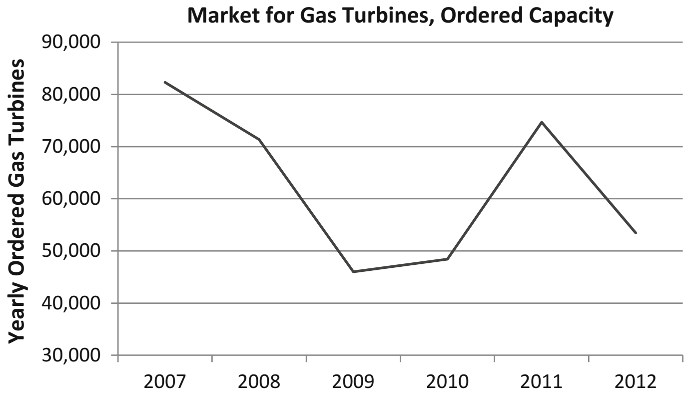

Fig. 5 Development of the market for gas turbine (Source: McCoy Data)

orders of gas turbines have been the United States, Saudi Arabia, Russia, China and Japan. With the exception of Japan, these are countries with domestic gas production and as a consequence at least moderate gas prices. However, about the half of the orders go to other countries (Fig. 5).

There are two typical project constellations for gas turbines. In the first constellation, the OEM only delivers the turbines for the power station. In this case, a third-party supplier does the construction and installation of the power station. In the alternative constellation, the OEM will also take over the construction and installation as general contractor. In addition to the sale of gas turbines, and possibly the construction and installation of the power station, service and maintenance is an important source of income for the OEMs. For the first few years, the OEM usually concludes a full-service contract with the client. Depending on the project's specification, these service contracts can have a volume of up to 50–70% of the initial price of the gas turbine or power plant.

As we have already described above, gas and steam turbine power stations are an important component of the worldwide power supply. The first operation of a gas turbine in a power station dates back to 1939, when a four MW gas turbine from BBC Brown were utilized in an emergency power station in Neuchatel in Switzerland. In the following years, the most important application of gas turbines was in jet engines, where it remains an important engine type until today. However, with the development of combined cycle power plants and increasing efficiency, gas turbines were increasingly used for electricity generation after the 1970s.

In recent decades, gas turbine series have been newly developed usually every 10–20 years. The Siemens E-class Gas Turbine, with a capacity of 150 MW, was developed in the seventies the F-class Gas Turbine, with a capacity of 250 MW, in the nineties. The series are mainly distinguished through their power range and the efficiency of the turbines. In a combined cycle power plant, the E-class Gas Turbine reached 450 MW with two gas turbines and an efficiency of about 50%. In its first version the F-class Gas Turbine reached a combined cycle efficiency of 56% with

705 MW, again with two gas turbines of a combined cycle power plant. For power plant operators as main clients for gas turbines, the power range and the efficiency are the most important characteristics of a gas turbine especially with respect to the operational expenses during the lifetime of the power plant.

Having reached the 55% mark of combined cycle efficiency, it appeared to be clear that the next technological step was the 60% mark of efficiency. All internationally renowned manufacturers strived for the 60% mark of efficiency. In the United States, the Department of Energy (DOE) funded the Advanced Turbine Systems Program (ATS Program), in which besides the market leader General Electrics, the second largest manufacturer of gas turbines in the US, Westinghouse, also participated with its unit Westinghouse Power Generation. From the middle of the nineties the competition in the power plant market continued to intensify. Worldwide, dramatic changes in the market could be expected driven by further liberalization and privatization of energy markets. Within this environment, Siemens wanted to strengthen its market position. In 1997, Siemens decided to buy its competitor Westinghouse Power Generation for converted EUR 1.33 billion. Westinghouse Power Generation employed 8000 people and had converted sales of EUR 1.9 billion in 1996.

With the takeover of Westinghouse Power Generation, the Siemens business unit for energy generation, the former Siemens KWU, became the second strongest player in the global market. The takeover opened up additional markets for Siemens power plants and gas turbines. Westinghouse Power Generation in particular had a strong position in the United States and Saudi Arabia. In summary, Siemens acquired well-developed technology, attractive market access, and grew significantly. On the other hand, after the takeover different technological concepts and solutions existed simultaneously in the same company. Most of the components for similar turbines were now available in two varieties. This increased the complexity in the Siemens gas turbines section significantly and caused additional costs.

This was one among several reasons why Siemens considered developing a completely new generation of gas turbines 10 years after the previous generation had been introduced. Technical evolution seemed to enable more modern gas turbines that better met the market demand and offered added value for customers. It had been 10 years since the introduction of the latest generation and, thus, the length of historic product life cycles suggested considering the development of a new generation of gas turbines. Additionally, General Electric had already announced to develop an H-class gas turbine. This announcement further raised the question whether Siemens also need to develop a larger and more efficient generation of gas turbines to remain competitive. A second argument specific to Siemens at the end of the nineties stimulated the impetus to create a new generation of gas turbines. The development of a new gas turbine generation would offer the opportunity to integrate Siemens and Westinghouse concepts into a common family and thereby lower the complexity resulting from the takeover of Westinghouse Power Generation.

Due to the long product life cycles and exceedingly high development costs, a generation of gas turbines is usually technologically upgraded several times during its lifetime. Individual components are developed further to maintain a technologically competitive product. Accordingly, the predecessor, the Siemens F-class Gas Turbine went through several upgrades: The initial version was, for example, used in 1996 in a combined cycle power plant in Didcot (United Kingdom). It reached an efficiency of about 56%. A later upgrade was used in a combined cycle power plant in Mainz in 2007 and reached an efficiency of over 58.5%. This improvement was reached without a general reconstruction of the gas turbine. In contrast to a technological upgrade of an existing generation of turbines, the development of a new generation means development from the ground up. In a later section, the most important technological decisions for the new gas turbine will be discussed.

To sum up, we identified several reasons for the development of a new gas turbine generation at Siemens. However, a resource-intensive and risky project such as the development of a new gas turbine generation must be carefully analyzed. The next section describes important elements of the decision-making process for the development of the H-class gas turbine at Siemens.

3.3 The Decision Process for the H-Class Gas Turbine

The development of a new generation of gas turbines is a highly resource-intensive project. Furthermore, the development process is extremely complex and is accompanied by many uncertainties. Thus, a careful decision and valuation process was necessary to enable Siemens to make an informed decision. The risk of losing out to the technological development of its competitors and the market-side chances of a new generation had to be traded-off against the investment expenditures that were necessary for the development process, and also the manifold risks that would affect the development decision. The investment decision and the whole development process were structured by a strict project plan divided into five distinct phases. The first phase was strategic product planning, which included the product strategy as the first step. In this planning phase, the main goals for development should be set and the initial development decision will be made. It comprises a definition and technical specification of the product to be developed as well as comprehensive market and risk analyses. The following paragraphs show the important steps and analyses that were conducted to reach the decision. Afterwards, the complete development process plan is outlined in greater detail, and the development process will be discussed.

Main Goals of the H-Class Gas Turbine Development

The first step in the product strategy phase of the decision process was to define the main development goals as precisely as possible. Firstly, this refers to technological specifications of the turbine generation that should be designed. It was also crucial to fix goals for the economic savings for potential buyers of the new H-class gas turbine. The liberalization of the energy markets, the privatization of the energy sector in many countries, and the increasing market penetration of renewable energy resulted in more complex customer requirements (see Fischer and Nag 2011; Ratliff et al. 2007). Firstly, liberalized energy markets increased the price pressure on the electricity generating industry. Therefore, a more cost-efficient power production was key for the power generating companies and increased their demand for efficient turbines and power plants. To meet this demand, Siemens aimed to reach a combined cycle net efficiency of over 60% that should result in about 3% of fuel savings. Furthermore, the specific investment costs (investment expenditure per produced kW power) had to be lower than for the predecessor.

Besides the savings in investment and operation expenses, the development of the H-class Gas Turbine aimed at a higher flexibility for the turbine's operation. The gas turbine alone should be at full power within <15 min. This is crucial if a combined cycle power plant is to be able to cover peak-loads that more frequently appear in electricity grids with a high share of renewably generated power. Moreover, for a highly flexible deployment of power plants, outstanding part load behavior is vital. In many countries companies are forced to lower their emissions. To address these requirements the newly developed turbine should have significantly reduced emissions per kWh produced. As outlined in Sect. 3.2, the service and maintenance of gas turbines plays an important role. A basic inspection is necessary every year, supplemented by several major revisions every 3–6 years. The relatively high frequency of inspection makes it necessary to allow for a serviceability with short outage times, which was defined as a further goal of the H-class turbine's development.

All in all, the new generation should minimize life cycle costs to increase the net present value for the power plant's owner. From the very beginning Siemens defined clear and highly ambitious aims. To achieve market success, the life cycle costs should be lowered by at least 7–8% compared to the previous gas turbine generation.

Market Analysis for the H-Class Gas Turbine

The next step for Siemens was to analyze the potential market for an H-class gas turbine, and to forecast how this market might develop over the next one or two decades. As in the whole period from 1991 to 2015, in the years prior to the decision by Siemens, the worldwide power supply grew by about 3% annually. Even more important are the growth rates for the years after the projected market launch of the new gas turbine generation. For the years 2015–2030 an only slightly slower growth in worldwide electricity generation was expected. For this period forecasts predicted an average annually growth of 2.5%, from 23,208 TWh in 2015 to 34,400 TWh in 2030.

It was not only the absolute amount of worldwide power supply that was an important factor for Siemens. Perhaps even more important for the decision was the forecasted development of gas-based electricity generation. This was expected to grow even faster than the total electricity generation. For potential sales number after the market launch, a key factor is how gas-based electricity generation will grow after the development is completed. Figure 6 shows a forecast for the development of shares in world electricity generation. Though renewables are

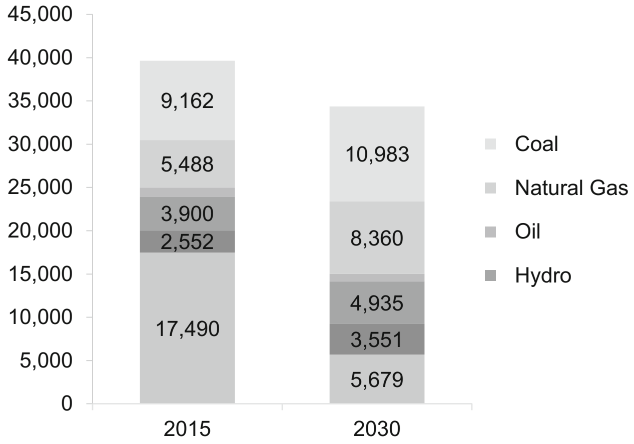

Fig. 6 World electricity generation (TWh) between 2015 and 2030 (Source: IHS Energy 2016, Rivalry scenario)

gaining in importance, there is still a forecasted increase in the share of gas-based electricity generation of 23–25% between 2012 and 2030. All in all, the development of the worldwide power supply suggested that there would be a promising market for a new class of gas turbines for Siemens.

Subsequently, Siemens went deeper into the detail and forecasted which capacity would be installed in 2012, which capacity should be installed in 2030, and which retirements of power plants are expected in the intervening period. With these data it was possible to calculate which new capacity additions would be necessary in the two decades after the projected market launch of the new gas turbine generation. Here we focus on the development of combined cycle power plants as the most efficient way of using the large gas turbine. The installed capacity in 2015 was 1605 GW worldwide. The expected development of the energy mix as it was described above leads to a forecasted worldwide installed capacity in combined cycle power plants of 2204 GW in 2030. With an expected retirement of 222 GW of installed capacity, one obtains new capacity additions of 821 GW between 2015 and 2030.

The revenues from a gas turbine or the whole combined cycle power plant greatly depend on the project specifications. A rough range for a combined cycle power plant is EUR 600–EUR 800 per kilowatt of installed capacity. In a pure gas power plant the price drops to EUR 200–EUR 400/kW installed capacity. Siemens' market share in the market for gas turbines was about 25% at the beginning of the past decade. Assuming a constant market share for Siemens, this would result in nearly 205 GW combined cycle power plants for Siemens out of a total capacity addition of 821 GW in the years between 2015 and 2030. These potential orders would equal a volume of EUR 144 billion. The development of a technically superior new generation of gas turbines might enable an even higher market share, and thereby even raise the potential market volume for Siemens.

Even though there clearly would be a market for modern gas turbines, and Siemens would be the first, after the failed attempt by General Electric in Baglan Bay with a gas turbine as large and as efficient as the planned Siemens H-class Gas Turbine, it was not certain whether market participants really would pay for such a large gas turbine. A market analysis reviewing the past and trying to forecast the future sales figures for different types and sizes of gas turbines in the market was conducted. The development as well as the forecast confirmed that there is a tendency towards larger gas turbines. All in all, Siemens concluded that the market for gas-based electricity generation is growing probably even faster than worldwide energy generation, which is expanding at a rate of around 2.5%. A significant number of new power plants using gas turbines would be required in the years following the projected market launch, and there seemed to be a market for larger and more efficient gas turbines. The market volume for gas turbines only in combined cycle power plants promised to be triple-digit billions over the lifetime of the new gas turbine generation.

However, in order to analyze the profitability of the development project, the forecasted revenues are traded-off against the expected investment expenditures for the project. An ex-ante estimation of the total investment expenditures is very complicated. A rough estimate of the investment expenditures for the development of the gas turbine’s 50-Hz-version was EUR 150 million. Another EUR 50 million were necessary to develop the 60-Hz-version. These numbers did not include any expenses for the very resource-intensive testing that would definitely be necessary after the development were completed to avoid nonconformance cost, which could be very high as they are usually contracted as a percentage of the overall contract for the power plant. The expected market success of the H-class Gas Turbine and the potential revenues would, however, justify these investment expenditures, but a careful analysis and assessment of all potential risks and uncertainties was considered crucial for the success of the Siemens project. In the following section we will outline and classify the most important sources and types of risk Siemens associated with the development project.

3.4 Identification and Assessment of Relevant Risks in the Project

A wide range of risks and uncertainties had to be taken into account for the project decision and—in the case of a positive project decision—managed. To ensure a systematic and comprehensive analysis of all significant risks in the project, they are classified according to the source of the risk. Here we differentiate market-related risks, technological risks, and other risks, such as political risks. Market-related risks refer to all uncertainties regarding the market success of the new gas turbine generation. Technological risks refer to uncertainties regarding the technical realization and the development process of the new gas turbine generation. The market estimations from the previous section are subject to considerable uncertainties. The most important and uncertain variables are the whole market volume, the market price level, and Siemens' market share. They all depend on a wide variety of influencing factors and variables that are unknown, and somewhat hard to predict. Siemens estimated the market volume by the development of worldwide energy demand and the share of gas-based electricity generation in respect of the total energy supply. Historically, the growth rate of worldwide energy demand shows some minor fluctuations, and indeed the growth rates for the second and third decade of the twenty-first century are forecasted to be slightly lower than they were in the last century.

However, the worldwide energy demand has steadily grown, and with fast-growing economies and the rising wealth in emerging countries, one can expect continuing growth in power demand at least for the lifecycle of a further gas turbine generation. More important, and harder to predict, is the share of gas-based electricity generation. An important factor for the long-term development of gas-based electricity generation is the price of natural gas itself. With rising gas-prices, the gas-based electricity generation would definitely lose in significance, whereas lower gas prices would raise the probability of an increase in the capacity of gas-based electricity generation. However, the prediction of actual gas price development is in general very hard. Besides gas price development, there are other important factors determining the importance of gas-based electricity generation. Of course, the price for other energy sources is another important factor. Increasing prices for coal or oil would make gas-based electricity generation economically more attractive. The development of more efficient power plants with other fuels, however, would make gas as an energy source less attractive. Regulatory changes with the goal of reducing fossil fuels that may also affect gas-based electricity generation might also be more likely. For example, in Germany regulatory changes influenced the economic profitability of gas-based power plants.

As described in Sect. 3.1, the unlimited priority feed-in and the subsidies for regenerative energy sources make the operation of gas-based power plants economically unprofitable during a large number of hours per year. The respective power plants are hard to finance with the remaining number of hours, where the price for electricity is high enough for economic operation of gas-based power plants. In summary, there are a lot of very different factors that influence the development of the gas-based electricity generation, such as the price of gas and its potential substitutes, the development of alternative technologies and the regulatory environment. Finally, with respect to the market volume and planned sales figures, one has to be aware that the market for gas turbines is usually cyclical in nature, with business cycles of between 2 and 5 years.

The development of the share of gas-based electricity generation on total power supply mainly determines the need for new gas-based power plants. However, besides the market volume for gas turbines, there is still uncertainty about the market share that Siemens can achieve. With the successful development of a new larger gas turbine and a combined cycle efficiency of more than 60%, Siemens would clearly achieve a first mover advantage that might ensure a stable or growing market share. If Siemens achieves the targeted cost savings for clients of 7–8% of lifecycle costs, it offers a competitive and attractive product. However, as described in Sect. 2.4, every important competitor was known to be aiming at the development of a more efficient large gas turbine breaking the all-important 60% combined cycle efficiency barrier. But such developments would make it even more important to develop an attractive product to stay in competition, and to mitigate the risk of being left behind the competition tomorrow.

The gas price is determined as an important risk factor for the market development of gas turbines. Whereas a low gas price is favorable for a high total market volume, this effect might be somewhat compensated by a countervailing effect on the market share for the H-class gas turbines: A high gas price increases the value of highly efficient gas turbines. The last important factor for the potential revenues from the new generation of gas turbines is the market price levels of gas turbines. In the past, gas turbines had been seen to be subject to strong price fluctuations of up to 30% in both directions around the long-term average.

The major uncertainties with respect to the market success of the new generation of gas turbines stems from the development of gas prices, its substitutes, changes in the regulatory environment, and the actions of the main competitors. The critical factor in ensuring a successful market launch generally is the technological success of the development process. Thus, besides the analysis of market-related risks, Siemens carefully analyzed the technological risks that would be related to the development of the new Siemens H-class Gas Turbine. Firstly, one can differentiate between technological risks during the development phase and risks after the market launch. First of all, it was uncertain whether the planned duration of development and thereby the planned investment expenditures could be realized. Large development projects tend to last longer than expected or become more expensive than planned. Furthermore, it was not sure whether the technical and economical specifications of the new gas turbine generation could be met. Siemens set itself strict and ambitious development goals. If for example the efficiency goals could not be met or their realization became more important in terms of development expenditures or production costs, the gas turbine can easily become less attractive to the market and, thus, less successful than expected. This shows that there are close interdependencies between the technological and the market-related risks.

There is a second category of technological risks that appears after the market launch of the product. If a new technology is not sufficiently tested and proven, there is a significant risk of high losses after the market launch. Product failures, necessary repair works and machine downtimes can result in high costs for the manufacturer and the client. Siemens and other OEMs had such experiences after the launch of the F-class gas turbines in the mid-nineties. The total failure costs amounted to many billions for manufacturers and power plant operators, and thereby exceed the original development costs many times over.

The only possibility of avoiding such excessive failure costs is an intensive testing phase. This is of particular importance because some components in gas turbines are too large to test separately before a prototype of the whole gas turbine is developed. The single construction and manufacturing of a large gas turbine is a very expensive project especially together with a whole power plant that is necessary to fully test a prototype gas turbine. The power plant together with the gas turbine can cost far more than a hundred million EUR. Among other reasons, due to these high costs OEMs usually sold a prototype to a power plant operator where it was used and simultaneously tested. The operator could sell the turbine's power with a discount, and in return the OEM obtained permission to run further tests with the sold turbine while it was in operation in a power plant. However, this frequently caused different problems. The major problems were conflicts about when the turbine could be tested while it was in operation. The power plant operator relied on a steady operation of the turbine whereas the OEM needed the turbine for tests and verification at certain points of time. Siemens deviated from this approach and tried to find a better solution to the testing phase of the H-class Siemens Gas Turbine. The stated aim was a comprehensive testing phase to approve the new technology and thereby avoid later failure costs.

Siemens decided to build a prototype after the development phase that should not be sold to a power plant operator right away. Instead Siemens entered into a cooperation agreement with the German plant operator E.ON. Together with E.ON, Siemens planned to build a gas-based power plant in Irsching, where the prototype of the new H-class Siemens Gas Turbine was to be tested over 18 months. During the testing phase the power plant is to be under the sole authority of Siemens. Of course this would cause further testing costs but it allows Siemens to extensively test the new gas turbine generation without having to take the ongoing operations of the power plant for the operator into consideration. After the 18 month testing phase, the power plant is to be expanded to a combined cycle power plant and afterwards it should be sold to E.ON. Hence, Siemens should be able to earn back a part of the investment expenditure for the testing power plant.

Risk Assessment for the Development Decision

Siemens used a wide range of analyses to evaluate the profitability of the development project, and the effect of the risk factors described in the previous section. This section gives an overview of the most important analyses. The key target figures that were considered during the analyses are the forecasted quantities of gas turbines to be sold, the profit margin, development expenditures, break-even numbers, and the time to break-even. Siemens conducted scenario analyses to analyze the effect of the gas price on the market volume, and thereby the product's success. Further, different scenarios for the competitors' behavior and the development of the competition were applied. Additionally, sensitivity analyses were applied. With sensitivity analyses, the effect of the market share, the market price level, and changes in the gas price on the profitability of the project were calculated. Siemens calculated threshold values of these primary variables for the time required to break-even.

The gas price has been identified as one of the most important market influences on the success of the planned gas turbine. The previous section has shown that high gas prices have a negative effect on the market volume, but can also have a positive effect on the market share of a highly efficient gas turbine, as the H-class turbine was planned to be. Until now, the gas prices in different regions of the world differ significantly. Due to the increased production volumes by hydraulic fracturing, the price for natural gas in Northern America may be significantly lower than prices in Central Europe. To take these differences in the market situations into account, the market volumes were separately calculated and forecasted for the different regions of the world. The importance of the gas price as a main factor in market development but also the role of increased efficiency in the gas turbine is underlined by the total cost of ownership (TCO) analysis of a gas turbine. On the basis of a 25-years product life cycle, the investment expenditures comprise only about 15% of the TCO. By far the largest part of the total ownership costs stems from the costs for the utilized gas. They can rise up to 70% of the TCO in times of high fuel prices. The remaining 15% are service costs and expenses that occur for the power plant operator. Following these calculations, the effect of an increase in efficiency by 1% can result in reduced life cycle costs of a base-load plant by EUR 30 million to EUR 50 million in markets or times where gas prices are high.

Besides the economic risks and uncertainties, there are substantial technological risks. These range from the risk of not achieving ambitious product characteristics to default costs for clients after the market launch. The risk management process for technological risks in the development process was guided by the Siemens Risk Assessment tool. The first phase of the risk assessment process aimed at identifying all the technological risks. The process started with a workshop that was moderated by process experts. Qualified engineers and experts tried to identify all relevant risks, such as default risks in certain components. It is not possible to completely avoid such risks and defaults. Hence, the risk management process aimed to mitigate the risk. The risks were classified as low, medium and high risks, depending on the risk level. The risk level was determined by the estimated probability of occurrence and the possible loss that can be caused by a default. From the beginning, all analyses aimed not just at the identification of risks but also at quantifying the costs for a default. For example, experts tried to calculate the days that a gas turbine fails in case of the failure of a certain component. Thereby, the monetary losses of such a failure could be calculated. Following particular development steps, the respective risks were regularly updated with new information that was gained during the development. Furthermore, the determined non-conformance costs were integrated into the business case to obtain a business plan that incorporates the technological risks as well as possible.

3.5 The Project Management and Managerial Flexibility in the Development Phase

After considering all relevant aspects for the profitability of the project and potentially related risks, Siemens decided to launch the program with the concept phase on October 1st, 2000. Along with a strict project plan, coherent program management is necessary for the success of a highly complex development program, such as the development of a new gas turbine. The development process plan was comprised of nine steps in five distinct phases, which described the primary functions within the business that had to be met in order to achieve successful developments. The main phases of the development process are strategic product planning, design, sales preparation, design implementation and validation. These phases reflect the main steps of Cooper's Stage-Gate Process (see Cooper 2002). The whole development process was strictly organized as a stage-gate process. Figure 7 shows the structure of the development process for the Siemens H-class Gas Turbine.

Either during or after each of the five stages described above, certain evaluations, called a gate, should be made. At these gates, decision-makers can make important decisions about the development project. Most importantly, the profitability of the project's continuation is reviewed. The first gate follows the determination of the product strategy during the strategic product planning stage. The second stage, the design phase, contains two steps, the conceptual design and the basic design phases.

Following the conceptual design, a second gate was set. During the third stage, sales preparation, the commercialization of the gas turbine was planned. This gate is followed by the third, the product release. The fourth gate should be the design

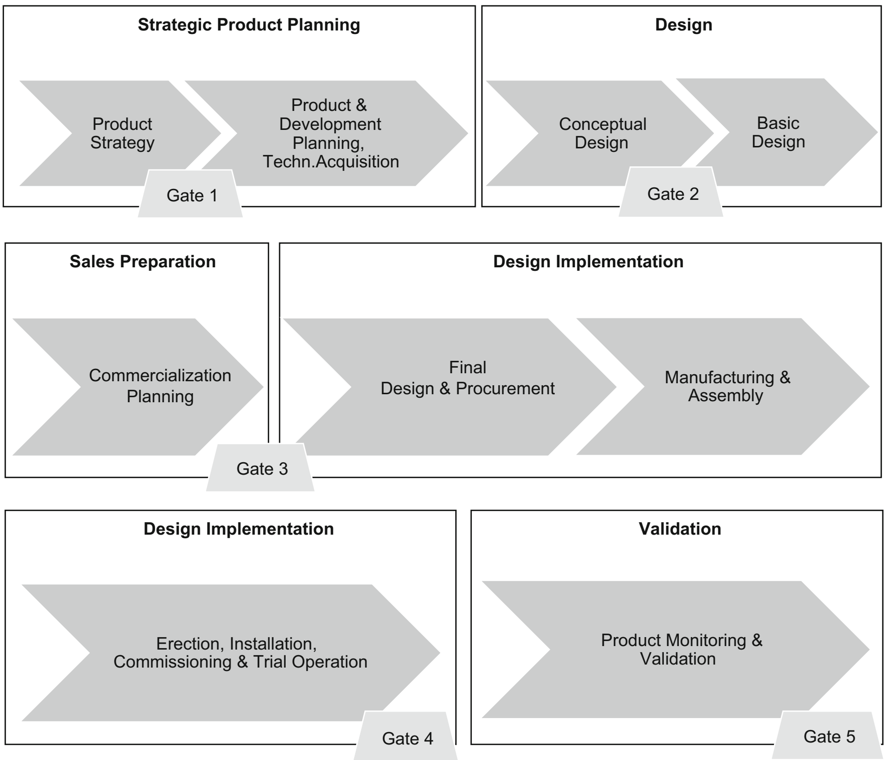

Fig. 7 The development process for the Siemens H-class Gas Turbine (Source: Siemens company data)

implementation. The first step in design implementation was the final design and procurement, followed by the manufacturing and assembly of the product. Design implementation should be completed by the erection, installation, commissioning and trial operation of the new turbine. Afterwards, in the fourth gate the series should be launched. The final stage is validation in which the product's performance is monitored and validated. After the final stage, the last gate signals the completion of the development phase.

At each gate a decision about the continuation of the development project must be made. In so doing Siemens enabled the flexible use of new information during the development process. These critical high-level decisions at predefined stages of the development process should ensure a regular re-examination of the success of the project and the market development. Only after this review and an explicit decision in favor of the project's continuation would new funds for the next development step be released. All of these gates represent options to discontinue the project. The gates are purposely chosen at specific points in the development process where particular information would become available that is important for the decision on continuation: For example, the determination of the product strategy that is followed by the first abandonment decision at gate one provides a preliminary indication of the potential market's attractiveness. For the second continuation decision following the conceptual design gate, there should be more clarity about the technological feasibility, the necessary development effort and the potential market development for gas turbines. After the commercialization planning, more detailed market data for the third abandonment decision should be available. Only if the financial outlook for the gas turbine in development is sufficiently positive would Siemens begin with the actual design implementation. The successful of the design implementation will be monitored for the fourth continuation decision. All mentioned gates entail a real option for Siemens. A growing body of literature analysis real option approaches in the energy and electricity sector (e.g., Fernandes et al. 2011 or Ceseña et al. 2013).

The Development Phase and Technological Flexibility

The H-class Gas Turbine development program was launched with the start of the first stage, the concept phase, on October 1st, 2000. The determination of the product strategy took 6 months and was completed with the product strategy release on March 21st, 2001. During the conceptual design phase which followed, the most important technological decisions were made: For each component all potential solutions were considered.

One of the most important technical decisions to be made was which engine cooling system should be used for the gas turbine. Engine cooling is important to ensure that the components along the path of the hot gas can withstand the high temperatures. Siemens had to evaluate whether steam-cooled technology was better than a completely air-cooled turbine. With a steam-cooled turbine, higher efficiency rates can be achieved. On the other hand, an air-cooled turbine has higher operating flexibility. The steam must be generated before the turbine can commence operation. The necessary generation of the steam leads to longer startup times. Furthermore, a steam-cooling system leads to higher technological complexity and increases the risk of failures. Siemens' main competitor, General Electric, had already begun developing a new generation of gas turbines with the declared target of a 60% efficiency rate. For this development General Electric relied on the steam-cooling technology.

For the previous generation, the Siemens F-class Gas Turbine, a purely air-cooled engine concept was used, while the latest gas turbine that Westinghouse had developed employed a combined air- and steam-cooled approach. In the industry, it was generally considered not possible to achieve such an efficiency rating with a purely air-cooled system. However, there were several future trends that some thought might make a more flexible operation of gas turbines favorable: More independent power producer projects and the expected increase in renewable power generation makes it necessary to have back-up power plants with a high operational flexibility to balance out fluctuations in decentralized or renewable power production. Flexible gas-based power plants are an important component for counter-balancing unexpected changes in renewably generated power. Trends such as decentralized and renewable power generation highlighted the necessity of flexible gas turbines. Additionally, Siemens asked its customers for feedback regarding the importance of high operational flexibility. These arguments ultimately led to the decision in favor of a completely air-based cooling system. Among other-decisions this was fixed at the second gate, which was concluded on November 5th, 2001. With this gate the basic design phase started which was finished with the third gate, the product release, on August 17th, 2004. The decision for the air-cooled engine concept demonstrates how Siemens used technical flexibility to respond to new trends that seemed to be developing.

The Testing Phase

Already in the early planning phase it had become evident that a gas turbine with more than 220 MW, which the H-Class Gas Turbine was designed to far exceed, could not be tested at Siemens' Berlin Test facility (see Fischer 2011). Thus, Siemens decided to cooperate with the large German electricity provider E.ON to launch a combined cycle project, to make it possible to test the gas turbine at the site in Irsching, a real plant environment with a grid connection. The infrastructure for a large combined cycle power plant already existed there. Moreover, it offered the possibility to increase capacity in Southern Germany to compensate for the newly installed wind power capacity in Northern Germany. Thus far, three gas-fired units have been installed in Irsching. Irsching I and II, built in the 1960s and 1970s, are no longer in operation, whereas Irsching III can still be used for peak load operation. As described above, the OEM of the gas turbines usually sold the prototype to a power plant operator and tested it in operation. However, this approach can lead to high breakdown costs and conflicts between the gas turbine manufacturer and the power plant operator regarding testing and operating times. To avoid such problems, Siemens decided to fully test the gas turbine series prior to the commercial market launch.

Siemens and E.ON negotiated a unique energy performance contract that provided for two phases. In the first phase only a simple cycle plant was to be constructed. During a following 18-months testing phase, Siemens would be given full flexibility to test the new gas turbine. In this phase Siemens were accountable for the operation of the plant. Siemens paid for the gas supply and sold the generated electricity. The first gas turbine for the new power plant Irsching IV was delivered by Siemens in April 2007 and was first fired in December 2007 (see Fischer and Nag 2011). During the 18-month testing and validation phase, Siemens conducted several measurement campaigns. Under ISO conditions the gas turbine has a rating of 375 MW, but it was loaded to over 400 MW during open cycle testing. On August 28th, 2009 the testing and validation phase was completed and with this completion the second phase of the contract between Siemens and E.ON began, the expansion of the Irsching IV plant to a combined cycle power plant. Construction was finished in January 2011, and during the next 6 months the combined cycle was tested. In July 2011 the plant was turned over to E.ON.

All of the original development goals were reached or even exceeded. The combined cycle power of the 50 Hz model in Irsching IV reached 578 MW with an efficiency of 60.75%. The emissions of NOx were lower than 25 ppm and the CO emissions were below 10 ppm. Furthermore, due to the pure air-cooling system high operation flexibility was achieved. The fast loading mode allows a start-up time of 10 min to 350 MW. A ramp down to a minimum load at 100 MW or complete shutdown is possible in <30 min. After a total planning, development and testing phase of more than 10 years, the handover of the Irsching IV power plant to E.ON marked the start of the first commercial operation of the Siemens H-class Gas Turbine. The first commercial order came from Florida Power & Light (FPL) for six Siemens H-Class Gas Turbines to modernize the FPL power plants in Cape Canaveral and Riviera Beach (see Fischer and Nag 2011). A second order came from the South Korean client GS Electric Power & Services. A fully turnkey 410 MW combined power plant was built in Bugok. By January of 2017, Siemens had sold a total of 80 H-class gas turbines. After more than 200,000 total operating hours of the worldwide H-class turbine fleet one can attest that the original technical goals could be fully reached. The fleet has a reliability of over 99% and achieves an efficiency level of over 60% in combined cycle power plants. Especially the short startup times and the fast load-changing capabilities make the H-class gas turbine attractive for the market.

3.6 Summary and Discussion

Investment decisions in innovative research and development projects are accompanied by a high degree of uncertainty, different risk types, managerial flexibility during the project lifetime, and, finally, investment expenditures that are usually irreversible. These characteristics make project decisions in research and development very difficult. Very high investment expenditures and a frequently long time lag between the investment expenditures and the market launch underscore the need for a well-analyzed allocation of scarce resources to projects in research and development.

At the beginning of the last decade, Siemens was considering the development of a new type of gas turbine. The technological development promised to enable larger and more efficient gas turbines, and the competitors had already started to develop new gas turbines. Additionally, the development of a whole new generation of gas turbines might have enabled the integration of Westinghouse technologies into a common family of gas turbines after Siemens' take-over of Westinghouse some years previously. Several global trends in energy markets required new technological solutions to better meet the increased demands of customers. In many countries liberalization and privatization of energy markets had increased the price pressure on power plant operators. Thus, power plant operators asked for more cost-efficient solutions. Moreover, trends toward more decentralized energy generation and the increasing importance of renewably generated electricity was accelerating the demand for highly flexible turbines and power stations. To meet the market demand, Siemens decided to set ambitious goals for the new product family in an early phase of the development process. The main goals were efficiency rates above 60%, a very high degree of flexibility with short ramp-up times and very good partial load behavior, and a reduced life-cycle cost for clients by 7–8% over the life time of the gas turbines.

The global growth and market outlooks were promising. Worldwide power demand was growing at nearly 3% annually and the share of gas-based production had also increased in past and was forecast to grow further after the planned market launch of the new gas turbine series. However, Siemens carefully analyzed all relevant risks prior to the development decision and identified a whole range of uncertainties in this process. Market-related risks mainly stemmed from uncertainties about the gas price, one of the most important primary variables. Furthermore, the actions of competitors, the development of worldwide power generation and of alternative sources of energy, as well as regulatory developments meant more uncertainty about market success and potential sales.

With the exception of the market-related risks, no substantial technological risks were identified. The most problematic risk is that the development goals cannot be realized at all or at least not with the planned expenditures. A delayed market launch or even the abandonment of development may be the consequence. However, in addition technical problems can cause high costs after a market launch. If the turbines are not sufficiently tested, long downtimes can cause high warranty costs. To lower and manage the technological risks Siemens applied the Siemens Risk Assessment tool. All relevant failure risks were identified and quantified in terms of the failure probability and potential downtimes and warranty costs. The risks were updated after all relevant development stages when new information emerged.

Besides the various types and sources of risks that had to be considered and managed during the decision and development process, Siemens had to make several decisions after the initial project decision. Classical capital budgeting theory usually assumes only one initial investment expenditure. However, in a research and development project the investment expenditures usually occur at several different stages. It is not necessary to spend all funds once the project decision is made. Such a project structure allows management to maintain flexibility in the project and even halting it if new information makes this advisable. Siemens explicitly considered this possibility utilizing a stage-gate-process. Five development stages were defined when the project was started, and for each stage a gate was defined. At each gate new information should be taken into consideration. From stage to stage, continuously improved information about market attractiveness, market development, technological feasibility, and development expenses should enable better abandonment or continuation decisions. An explicit continuation decision is necessary to commence with the next stage and spend the related funds.

The project was initially started on October 1st, 2000. In March 2001 the product strategy was defined and the conceptual design phase was started after the market attractiveness of the planned gas turbine was confirmed. During the conceptual phase, the main technological decisions should be made. In addition to the managerial flexibility to abandon the project at a number of stages, Siemens enjoyed a lot of technological flexibility in the development process. During the early development phase, it became more and more obvious that higher operational flexibility of combined cycle power plants would be necessary in the future. One way to obtain higher operational flexibility was to use a pure air-cooling system instead of a steam-cooling system. Though this made achieving the ambitious efficiency goals more complicated, Siemens decided to use a completely air-cooled concept.

The development project took 7 years, and the first gas turbine was delivered in April 2007 for testing. To avoid high failure and warranty costs, Siemens decided to start an innovative cooperation project with the German power plant operator E.ON to test the newly developed gas turbine. In Irsching a new power plant was built to test and validate the first H-class Gas Turbine. In an 18-month testing phase, Siemens was solely responsible for the operation of the power plant and could test it in a real plant environment with a grid connection. After the successful testing phase, the power plant was extended to a combined cycle power plant. All development goals were reached or exceeded. In a world record run, it reached 578 MW with an efficiency of 60.75%. The combined cycle power plant was finally sold and has been operated by E.ON ever since. However, due to the comparably high gas prices and the increased share of renewable energies in Germany it now operates as a backup power plant to ensure a high level of grid stability. The takeover of the power plant by E.ON meant the completion of a more than 10 years development phase for the Siemens H-class Gas Turbine, which had sold 80 times by January 2017.

The case of the Siemens H-class Gas Turbine demonstrated how to successfully perform a complex development project in a highly uncertain environment. The development and the market launch was a great success for Siemens. Today, the competitors have also developed H-class gas turbines with efficiencies of more than 60%, but Siemens still holds a strong position in the market. To maintain its competitive advantage and to offer a superior product to its clients, Siemens will continue to further enhance the performance of the Siemens H-class Gas Turbine. Efficiency of more than 63% is currently targeted by Siemens and its competitors. Due to the very long product life cycles, the Siemens H-class Gas Turbine will remain a key product for Siemens in the gas turbine market.

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