A MULTIPERIOD OPTIMIZATION MODEL TO SCHEDULE LARGE-SCALE PETROLEUM DEVELOPMENT PROJECTS

A Dissertation

by

MOHAMMED HAMZA HUSNI

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2008

Major Subject: Petroleum Engineering

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Approved by:

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ABSTRACT

A Multiperiod Optimization Model to Schedule Large-Scale Petroleum Development Projects. (December 2008)

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This dissertation solves an optimization problem in the area of scheduling large-scale petroleum development projects under several resources constraints. The dissertation focuses on the application of a metaheuristic search Genetic Algorithm (GA) in solving the problem. The GA is a global search method inspired by natural evolution. The method is widely applied to solve complex and sizable problems that are difficult to solve using exact optimization methods. A classical resource allocation problem in operations research known under Knapsack Problems (KP) is considered for the formulation of the problem.

Motivation of the present work was initiated by certain petroleum development scheduling problem in which large-scale investment projects are to be selected subject to a number of resources constraints in several periods. The constraints may occur from limitations in various resources such as capital budgets, operating budgets, and drilling rigs. The model also accounts for a number of assumptions and business rules encountered in the application that motivated this work. The model uses an economic performance objective to maximize the sum of Net Present Value (NPV) of selected projects over a planning horizon subject to constraints involving discrete time dependent variables.

Computational experiments of 30 projects illustrate the performance of the model. The application example is only illustrative of the model and does not reveal real data. A Greedy algorithm was first utilized to construct an initial estimate of the objective function. GA was implemented to improve the solution and investigate resources constraints and their effect on the assets value.

The timing and order of investment decisions under constraints have the prominent effect on the economic performance of the assets. The application of an integrated optimization model provides means to maximize the financial value of the assets, efficiently allocate limited resources and to analyze more scheduling alternatives in less time.

To my beloved mother and wife for their patience and support,

and to my family and friends.

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CHAPTER I

INTRODUCTION

The role of Exploration and Production (E&P) sector of oil and gas industry is to engage in the upstream business activities of oil and natural gas that maximize economic performance. This complex task can be managed by proper application of optimization methods to select and schedule these activities over the business planning horizon. The optimization methods involve maximizing or minimizing an objective function bounded by a set of specific constraints. The objective function incorporates the appropriate choice of a financial measure such as profit or cost. The constraints may occur due to limitations in technical, operational and financial resources in addition to strategic goals and business rules.

Early applications of optimization methods in the upstream sector of oil and gas industry focused on investment decisions within individual or small number of development and expansion projects. This work presents an integrated novel model to maximize financial performance of numerous large-scale petroleum development and expansion projects with multiple resources constraints in multiperiod planning horizon.

This dissertation follows the style and format of *SPE Journal.*

The exponential behavior of this scheduling problem imposes computational challenge. The difficulty of determining an optimal solution to this problem in polynomial time is bordered by the number of activities of numerous projects and the number of different types of limited resources. The complexity expands with the number of periods of the planning horizon. In view of this exponential complexity, it becomes infeasible to attempt enumerating all possible combinations to efficiently allocate several resources to satisfy the various activities of all projects and assure availability limits of every resource in multiple periods.

1.1 The Motives

The world has encountered considerable increases in energy prices which inspires a significant interest in energy research. The availability of energy is essential to sustain and develop global economies. Most forecasts project increasing demand for energy as populations and economies expand. The Energy Information Administration (EIA) projects growth in world demand for energy exceeding 50% by year 2030, as shown in **Fig. 1.1**. This projection assumes growing populations and economic activities. According to the United Nations (UN), the world population has increased from 2.5 billion in 1950 to approximately 6.7 billion today. This population growth will continue to increase to reach at least 8 billion by the year 2050 as projected in **Fig. 1.2**.

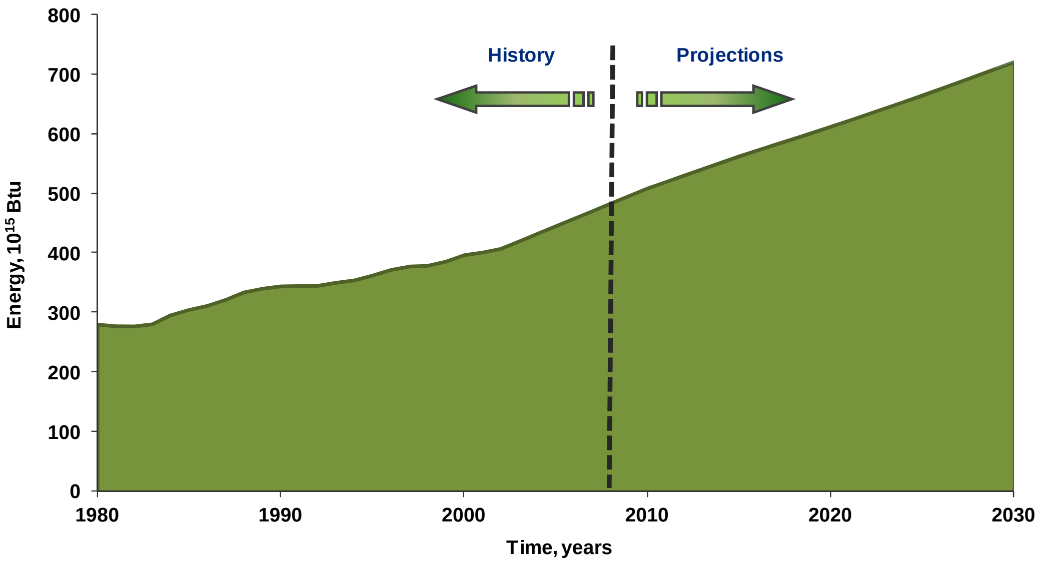


Fig. 1.1—Global energy consumption outlook.

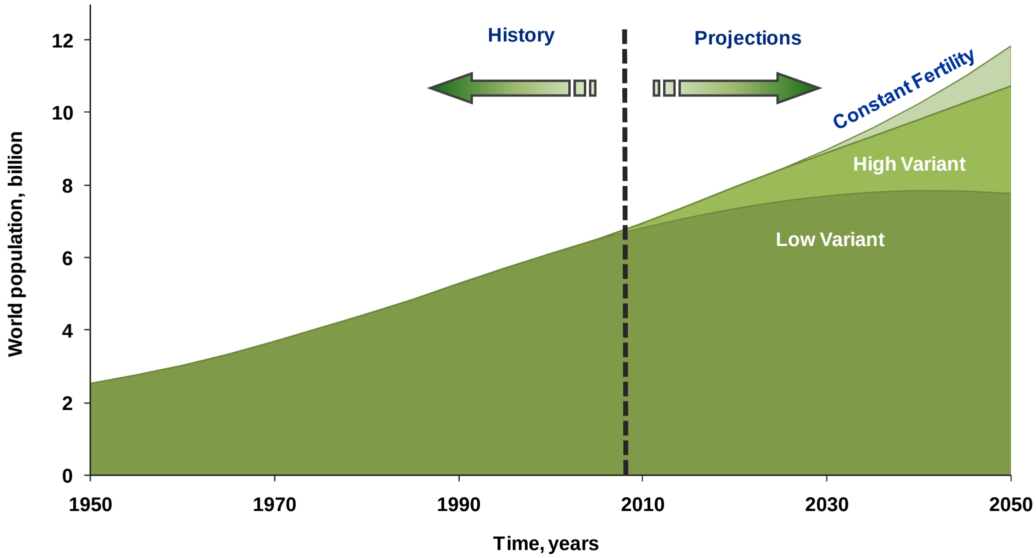


Fig. 1.2—World population projection by UN.

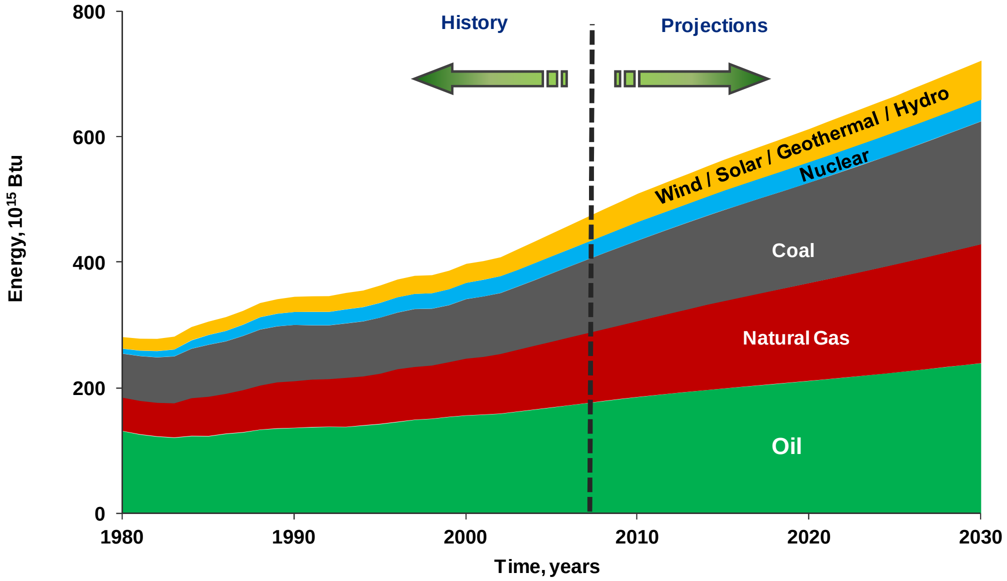


Fig. 1.3—Energy allocation forecast.

A study report by the National Petroleum Council (2007) entitled Facing the Hard Truths about Energy stated that the world currently uses various energy sources and expansions of all these sources are required to meet the world demand. According to the study, fossil fuel (coal, oil and natural gas) dominates the projected energy production. **Fig. 1.3**, from the EIA, projects the distribution of various energy sources. The figure demonstrates that most of the increases in consumption will be met by increases in the supply of fossil fuel. Oil and natural gas are two vital energy sources which contribute 60% of world supply of energy with future development potential. Expansion of coal production will increase CO_2 emissions since coal produces more CO_2 per unit of energy than natural gas and oil. There are growing concerns of CO_2 and its role in climate change which may lead to constraints on carbon emissions. Environmental viability of coal expansion requires developing new technologies to effectively manage carbon emissions at lower-costs. A potential technology for reducing CO_2 emissions is carbon capture and sequestration, which captures CO_2 and keeps it underground. Coal development faces further environmental and infrastructure limitations including water use, land use, transportation and waste disposal. This makes expansions of oil and natural gas more viable to meet the increasing demand for energy. **Fig. 1.4** shows projected emissions of CO_2 from coal, oil and natural gas.

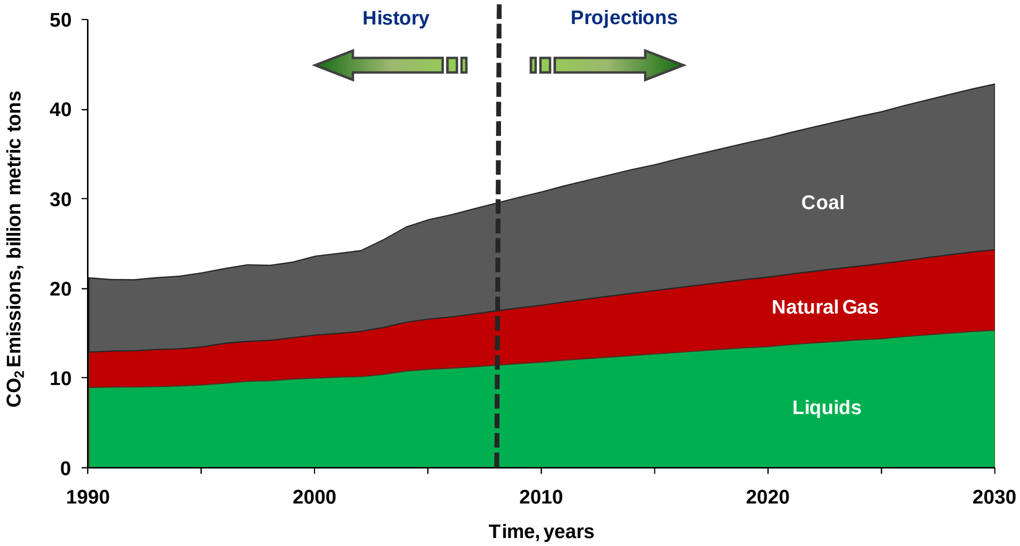


Fig. 1.4—Energy related CO_2 emissions by fuel type.

In recent years, petroleum development projects costs have increased significantly which may raise concerns in investment planning and availability of capital budgeting. This includes costs of rigs, facilities, equipment, offshore vessels and labor. An E&P spending survey from 247 oil and gas companies, by Kieburtz et al. (2008) from Citi

Investment Research (CIR), projects 9.3% expenditures increases from USD 324.4 billion in 2007 to USD 354.6 billion in 2008. The E&P spending outside North America is expected to reach USD 240.4 billion. Spending in North America is estimated to rise to USD 114.2 billion. This creates a great economic potential in E&P investment optimization worldwide. **Fig. 1.5** from OPEC (2008) depicts E&P investments and the number of projects of OPEC member countries excluding Iraq.

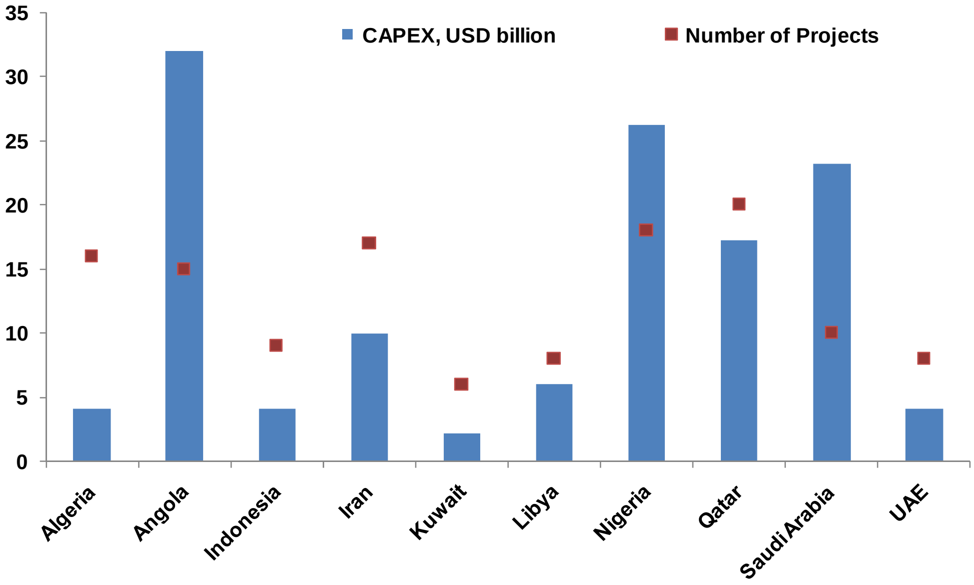


Fig. 1.5—Upstream investment plans of OPEC countries.

The shortage of talented manpower in the oil industry presents a workforce challenge. The average age of the members in the Society of Petroleum Engineering (SPE) is growing to 48 years with 40% of the members above 50 years old (**Fig. 1.6**). These statistics indicate that a considerable portion of the experienced workforce may leave the industry within 10 years based on current retirement policies of many companies. This requires mapping future gaps between current workforce and future requirements and developing talent management strategies to face this workforce challenge as the industry enters a period of business expansion.

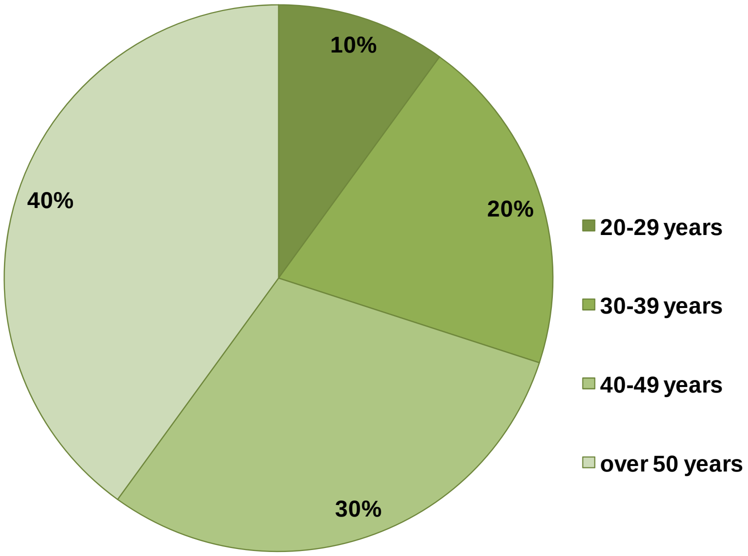


Fig. 1.6—SPE members demographics.

1.2 Objectives

The objective of this research work is to formulate and develop an optimization model for selecting and scheduling large-scale petroleum development and expansion projects subject to a number of well-defined constraints along a multiperiod planning horizon. The following specific tasks will be considered to accomplish this objective.

- Formulate the problem.

- Design a problem-specific algorithm.
- Evaluate economic performance of proposed development and expansion projects.
- Write the algorithm code to solve the multiperiod multiple constraints optimization model.
- Test the algorithm using synthetic data which has characteristics similar to those in the application that motivated this work.

The research developed in this dissertation should help oil and gas business planners to:

- Optimize the selection and scheduling of petroleum development and expansion projects along a planning horizon.
- Make more effective and consistent decisions to improve assets value bounded by multiple constraints.
- Analyze more investment options in an integrated framework in less time.
- Improve planning workflow, meet strategic goals and capture technical, operational and financial constraints.

1.3 Literature Review

A range of mathematical optimization methods were applied in the upstream sector of oil and gas industry to improve economic value of petroleum development projects. This literature review highlights major deterministic models dealing with the optimization of petroleum development planning.

Several comprehensive mathematical programming formulations have been proposed for oil field development planning problems. Generally linear approximation is used to estimate the nonlinear behavior of the reservoir. The formulation can be quite complex and problem specific. The integer variables are usually handled using branch and bound method. Lee and Aronofsky (1958) described a simple Linear Programming (LP) method for scheduling oil production from five sources of a single reservoir to maximize net profit. A linear equation relating pressure drop to production rate was estimated from superposition of influence coefficients (derived from sequential unit rate production of all but producing wells and recording of pressures). Two separate LP models were proposed later by Aronofsky and Williams (1962). The first model optimized scheduling of field drilling for a predetermined production rate. The second model optimized scheduling of production rate for a fixed drilling schedule. Bohannon (1970) proposed a Mixed Integer Linear Programming (MILP) model to plan annual production rate, wells requirements, and major investments schedule for multiple oil reservoirs over 15-year planning horizon.

Heuristics approach has been applied extensively to solve optimization problems in the oil and gas development planning. Devine and Lesso (1972) proposed a heuristic algorithm for the sizing and location of offshore platforms to minimize investment. This work was expanded by Frair and Devine (1975) to include the well drilling and production rate of each reservoir. This was managed by decomposing the problem into two independent sub-problems. One sub-problem deals with platforms locations and wells allocations. The other sub-problem handles well scheduling. The decomposition approach became less accepted as it fails to guarantee global optimality. Lilien (1973) highlighted the need for including sequential decision procedure to account for the added knowledge by each well because of geological dependency. Dogru (1975) represented the problem of optimal development of offshore oil fields as a Mixed Integer Nonlinear Programming (MINLP). She proposed several heuristic methods to maximize the NPV.

Later, Sullivan (1982) developed a MILP planning model to maximize the economic worth of three offshore gas reservoirs. Each reservoir performance equation was described linearly using piecewise interpolation. The model included taxes and royalties in each period but as fixed percentage of some economic measure to avoid computation complexity. Grimmett and Startzman (1988) used a branch and bound method to minimize investments when selecting, sizing, and locating major offshore production facilities. The model included the allocation of wells to these facilities. The application of these models was limited due to long solution times when solving real world problems. Garcia-Diaz et al. (1996) used branch and bound method with Lagrangian relaxation to generate lower bound which reduces computation time and allows application to actual offshore field development problems. Bittencourt (1997) proposed several heuristics with hybrid GA as the main approach. He built an interface with a commercial simulator which was used to generate production profiles. The model was used to determine well locations for an oil development project to maximize NPV. Harding et al. (1998) also used GA to schedule group of linked oil and gas fields to maximize NPV.

Iyer et al. (1998) proposed a sequential decomposition algorithm to solve multiperiod MILP problem for planning and scheduling of investments and operations in offshore oil field. The objective was to maximize NPV considering multiple reservoir development options, well drilling schedule, pressure performance of each well from reservoir simulation, and facilities capacity constraints. The reservoir performance was linearly described using piecewise interpolation as in Sullivan model. Van den Heever et al. (2000a, 2000b, and 2001) proposed various models to solve offshore development planning problems. Van den Heever et al. (2000a) solved the MINLP problem for planning oil reservoir development using a logic-based iterative aggregation/disaggregation algorithm. The model determines platform location and capacity in addition to well allocation and schedule. Van Den Heever et al. (2000b) directly incorporated the nonlinear behavior of the reservoir system into the model for a multiperiod MINLP. Van Den Heever et al. (2001) proposed a heuristic algorithm based on Lagrangian decomposition to solve the same multiperiod MINLP model for the long-term design and planning of offshore oilfield development. The model allows solving the very complicated problem which arises from including complex fiscal rules such as taxes, tariffs, and royalties. Ortiz-Gomez et al. (2002) described three multiperiod optimization models: simplified MILP, MINLP with production at capacity, and MINLP with cyclic production. The three models were solved for short-term planning of oil production in wells. The two MINLP models incorporated the nonlinear behavior for the well flowing pressure while calculating oil production rate. Both models fail to guarantee global optimality. The authors concluded with the need to further investigate the global optimality of the algorithms. Carvalho and Pinto (2006) used the same disaggregation technique used by Iyer et al. (1998) to solve the MINLP model for planning of platforms locations, wells allocation, drilling schedule and production rate in an offshore oil field. The model is composed of a master problem which determines assignment of platforms to wells and a sub-problem which schedules drilling of the wells. Luedtke (2007) studied a multiperiod strategic planning model for oil fields development with start-time dependent variable costs to account for technology improvement over time. The formulation was based on a number of MILP and a branch-and-cut algorithm was proposed to solve large-scale instances. The proposed models assumes deterministic data to avoid the challenge of studying uncertainties of large scale instances in multiperiod and modeling technology improvement overtime. The computational results of the model were shown with no details of the application.

The previous work involves applying optimization methods to petroleum field development to accomplish the following planning activities.

- Production planning and scheduling.
- Location of major facilities and allocation of wells to these facilities.
- Multiperiod planning and scheduling of investments and operations.

The studies were limited to single or multiple reservoirs of small to medium size. These reservoirs are usually located within a field or a number of neighboring fields in a region.

Dougherty et al. (1986) used mathematical decomposition with iterative techniques to optimally solve investments in gas production system over a planning period. The paper indicated that the system was successful in planning annual investments and operating budgets in a producing complex with no details of results. Seba (1987) discussed applying the ratio of NPV to capital investment (NPVI) to rank and select petroleum investments in the presence of capital limitation. Hartsock (1987) discussed Seba paper and the limitations of NPVI method. He briefly pointed the capital rationing problem proposed by Lorie and Savage (1955) and the integer linear programming solution by Weingartner (1963). The in-depth literature search did not reveal direct research efforts to deal with optimizing petroleum development projects selection schedule of large-scale instances with multiple constraints along multiperiod planning horizon.

This research work presents an actual industrial challenge, where appropriate management and planning is required to maximize the assets value of considerable amount of developed and undeveloped hydrocarbon reserves. The work intends to develop a deterministic model to optimize selection schedule of projects to maximize economic value of hydrocarbon reserves over planning horizon. These projects are irreversible and require intensive technical, financial, and operational resources. The model involves multiple scarce resources, production target, onshore and offshore fields, and problem-specific strategies and business rules. The model should have the capacity to deal with production system of a scale of several millions barrels per day.

1.4 Dissertation Outline

The dissertation is divided into six chapters. Chapter II defines the problem of multiperiod optimization model to schedule large-scale petroleum development projects. The chapter will also discuss Knapsack Problems (KP) which are resource allocation problems. This is an important class of combinatorial optimization which will be used as basis of formulation. The chapter also introduces the mathematical programming formulation of the model.

Chapter III introduces the optimization model and solution approach. The model is developed to study actual industrial problems of managing hydrocarbon reserves development and planning. The metaheuristic method of GA is discussed and implemented to search for global solution.

Chapter IV discusses main characteristics of large-scale petroleum projects. The chapter illustrates cash flow streams and rig-year requirements for 30 development and expansion projects. These projects will be considered to demonstrate the model solution.

Chapter V illustrates the performance of the proposed model through the 30 projects example subject to several constraints. The chapter incorporates a number of cases including low and high prices cases.

Chapter VI presents the conclusions of the work with directions for future research. In addition to the six chapters, projections of oil and gas prices of various projects are provided in the appendix.

CHAPTER II

PROBLEM DEFINITION

2.1 Problem Definition

Project scheduling is a decision-making process of allocating scarce resources to investments over time. The problem of optimizing upstream investments in an oil company is defined here as the decision problem of scheduling the selection of development and expansion projects to maximize assets value. The projects are characterized by scarce resources, strategic considerations, and business rules.

The proposed optimization model of projects scheduling involves the selection of the startup of large-scale petroleum development and expansion projects over multiperiod planning horizon. The problem is multiperiod because of variations in production of oil and gas, escalated costs of development and operation, and unstable market prices from period to period across the planning horizon. The model considers the following assumptions.

- Production strategy of oil and gas projects is defined with an average production rate in each period and possible variation from one period to another over a given planning horizon.
- The model accounts for various limitations in resources such as capital budgets, operating budgets and drilling rigs.

- Projects are irreversible. Selected projects will remain active over the entire planning horizon.
- Projects may include a number of options to develop or expand a field which is composed of one or more hydrocarbon reservoirs producing into a production system. The options may differ in capacity, development concept and technology, operating cost, and product blend.
- Features of large-scale petroleum projects in a regional complex similar to those in the Middle East are considered.

The evaluation of petroleum development and expansion projects involves geological and simulation studies of the reservoirs. The reservoir simulation has become a standard practice in reservoir development and expansion studies. The main objective of a simulation study is to make production forecast. The evaluation also involves the design and operation of the required production system. The following list presents the main decisions related to the design and operation of a production system.

- Number and location of production and injection wells.
- Number, type, size and location of production facilities.
- Allocation of wells to facilities.
- Scheduling of wells and facilities.
- Production and injection rates.
- Enhanced recovery.
- Abandonment of field.

As discussed in the introductory chapter, several development planning models were proposed to optimize the development of single or multiple hydrocarbon reservoirs. These models showed various successes in relating the performance of the reservoir system to the productivity of the wells and the flowing of fluid in the surface production system.

A typical study of a petroleum development or expansion project will provide the following outcomes to evaluate the economic performance of the project.

- Production forecast of oil, gas and water.
- Required injection rate of water or gas.
- Production and injection drilling requirements.
- Capital investments on wells and production facilities.
- Operating costs.

Fig. 2.1 depicts a schematic of a project streams showing the 20-year profile of production rates, capital and operating costs, and onshore and offshore drilling requirements. These outcomes of individual development and expansion studies are assumed to be known. They will be provided as input to the proposed model to maximize the financial performance of the assets based on feasible ordering and timing of selected projects. The objective is to maximize the aggregated NPV of the selected projects subject to specific constraints over the entire planning horizon. The development of large-scale petroleum projects requires substantial amount of financial, operational, and technical resources. The model should have the capability to allocate a number of limited resources among competing projects. **Fig. 2.2** depicts an overview of the interactions within the proposed model.

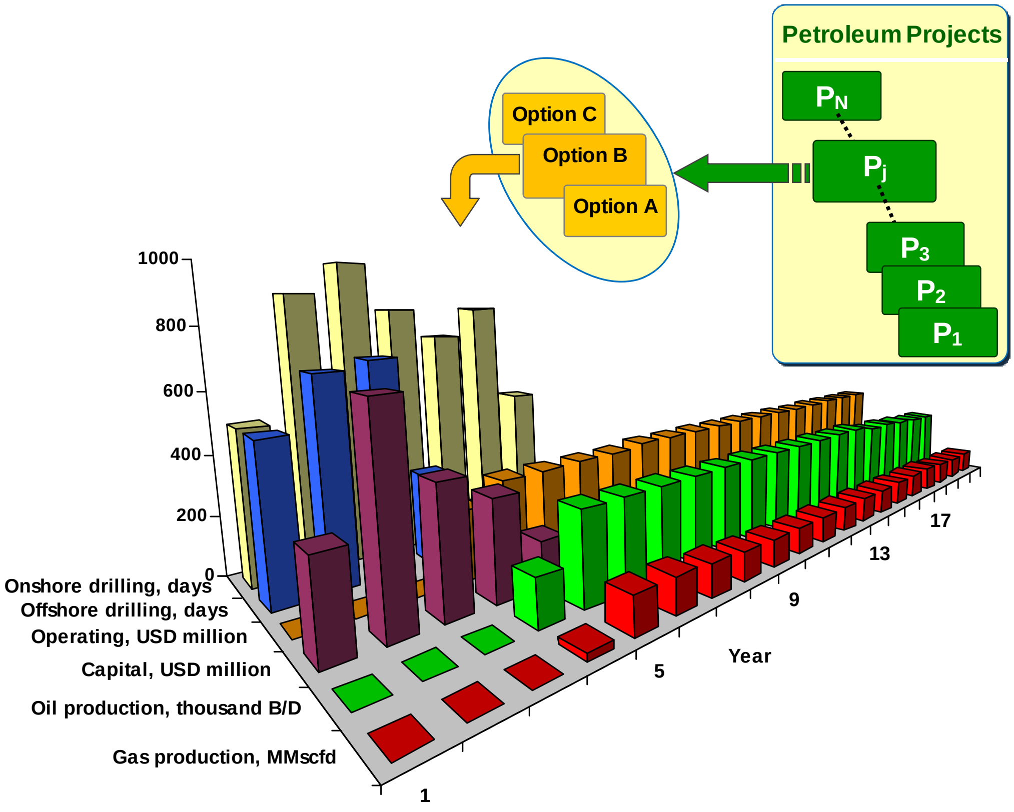


Fig. 2.1—Various streams of a petroleum development project.

The challenge for the work reported in this document is to develop a corporate level model to maximize economic performance, efficiently use capital and other resources, and meet corporate strategies and guidelines. In view of the large number of decision variables, the enumeration of all possible combinations is not feasible to attempt. The model should also have the capability to include several optimized development options of various production strategies. This type of scheduling problems is very similar to a Multi-Dimensional (multi-constrained) Multiple (multiperiod) Knapsack Problem (MDMKP).

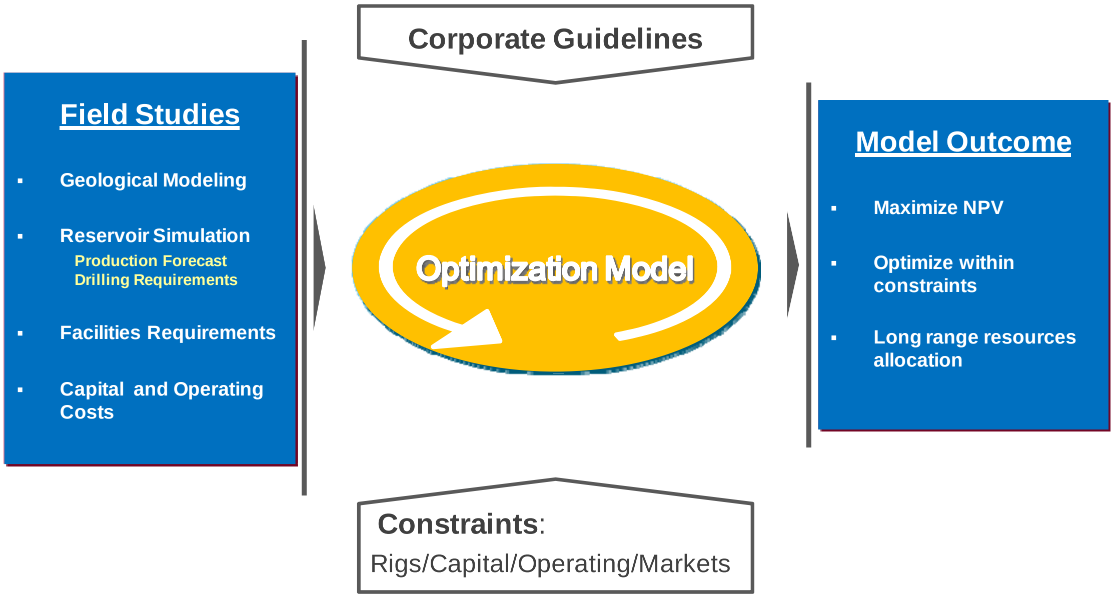


Fig. 2.2—Model interactions.

2.2 Knapsack Problems

Knapsack Problems (KP) are resource allocation problems where limited resources have to be optimally allocated among a set of activities. The knapsack problems become well-known after the pioneering work of Dantzg in the late 1950's. According to Pisinger (1995), all knapsack problems belong to a family of NP-hard combinatorial optimization problems. This means that devising polynomial algorithms for these problems is very unlikely. The size of the instance exponentially affects the time requirement for optimal solution. After several decades of research, however, many of the practical occurring instances become solvable in reasonable time. The following recognized techniques were used to solve many of the knapsack problems to optimality or near optimality.

- **Branch and Bound**

Branch and Bound (B&B) is an exact method which is widely used for solving NP-hard combinatorial optimization problems. The method was first described by Land and Doig (1960) for linear programming. The feasible region of a problem is first divided into a B&B tree of smaller sub-regions. The method reduces the search space by pruning the search along a particular branch if some limit or bound is exceeded. The method does not prune the solution along any branch until it makes sure that the optimal solution cannot occur along that branch. The efficiency of the method depends strongly on the branching and bounding procedures. The major difficulty with the branch and bound method is the lack of optimality conditions to verify whether a solution is optimal or not. Therefore, all feasible solutions should be compared to guarantee optimality. Therefore, computation time can become exhaustive in large and complex problems.

- **Dynamic Programming**

Dynamic programming (DP) is a powerful technique which was first developed by Richard Bellman (1957) to solve certain types of decision and optimization problems. The methodology decomposes the problem into a sequence of separate stages or sub-problems which are interrelated decisions or optimization steps. The optimal solution of the problem is then computed by recombining the solutions of the sub-problems. Backward recursion is considered to be the most common computational procedure. DP is considered as a good technique for many practical optimization problems due to the sequential decision making and ease in handling nonlinear objective functions and constraints. However, the application of DP can become limited due to the ‘curse of dimensionality’, which is the exponential computational explosion with the increase in dimension.

- **Dynamic Programming Relaxation**

The coefficients are scaled by a certain value which decreases the time and space of an algorithm considerably. This leads to efficient approximation using dynamic programming method.

- **Metaheuristics**

Various metaheuristics like Tabu Search, Simulated Annealing, Neural Network, and Genetic Algorithms are widely used to find the near-optimal solutions. Well-devised metaheuristic can provide effective and efficient solutions for many problems that are too large and complicated to be solved by traditional methods. The aim of metaheuristic methods is to quickly produce good-quality solutions. In many real life cases, obtaining an exact optimal solution is not essential, since we are often dealing with models that are rough approximations of reality. As in any artificial intelligence method, experimentation with the algorithm is required to improve the quality of a solution and its proximity to optimality.

2.3 Variants of Knapsack Problems

This section demonstrates the main variants of the family of knapsack problems as described in Kellerer et al. (2004) and Pisinger (1995). The simplest type of knapsack problems is the classical knapsack problem which is the problem of assigning a set of n items to a knapsack of certain capacity c. Each item j is described by a profit p_j and a weight w_j. The problem is to select the items to place in the knapsack, such that the total profit is maximized and the capacity constraint is satisfied. Thus, the classical knapsack problem can be formulated by the following integer program:

$$\begin{aligned} &\text{maximize} && \sum_{j=1}^{n} p_j \quad x_j \\ &\text{subject to} && \sum_{j=1}^{n} w_j \quad x_j \ \le \ c \qquad\qquad 3.1 \\ & && \mathrm{x}_j \ \text{ is a non-negative integer, } \ j = 1, \ldots, n. \end{aligned}$$

Dynamic Programming can be used to solve the above problem in pseudo-polynomial time. A recursion of dynamic programming method can be applied after breaking up the problem into stages or sub-problems. Dantzig (1957) found an elegant way to solve the above problem by sorting the items according to their profit-to-weight ratio.

$$\frac{p_1}{w_1} \ \ge \ \frac{p_1}{w_1} \ \ge \ \ldots \ \ge \ \frac{p_1}{w_1} \qquad 3.2$$

The computed ratios are arranged in non-increasing order and a greedy algorithm can be used to obtain a solution of the problem in pseudo-polynomial time. The idea of the greedy algorithm is to add items of largest ratio into the knapsack in each step until the capacity is reached.

The classical 0-1 knapsack problem involves selecting n items or projects to maximize total profit without exceeding the knapsack capacity c. The model can be formulated as follow:

$$\begin{aligned} &\text{maximize} && \sum_{j=1}^{n} p_j \quad x_j \\ &\text{subject to} && \sum_{j=1}^{n} w_j \quad x_j \ \leq \ c \qquad\qquad 3.3 \\ & && x_j \in \{0,1\}, \quad j = 1,\dots,n. \end{aligned}$$

where x_j is a binary decision variable. The item or project j should be placed in the knapsack if the decision variable equals 1, and 0 otherwise. Exact solution for this problem can be found using dynamic programming or branch and bound method.

The 0-1 Multiple Knapsack Problem (MKP) is a variant of the classical 0-1 knapsack problem where the knapsack involves assigning n items or projects to m distinct knapsacks to maximize total profit without exceeding the capacity of each of the knapsacks. Consider a problem where n items or projects have to be placed in m knapsacks of distinct capacities c_i. The MKP can be stated as the following integer linear program:

$$\text{maximize} \quad \sum_{i=1}^{m} \sum_{j=1}^{n} p_j \quad x_{ij}$$

$$\text{subject to} \quad \sum_{j=1}^{n} w_j \quad x_{ij} \ \leq \ c_i$$

$$\sum_{i=1}^{m} x_{ij} \ \leq \ 1 \qquad 3.4$$

$$\mathrm{x}_{ij} \in \{0,1\}, \quad i = 1,\ldots,m, \quad j = 1,\ldots,n.$$

The problem has several applications in cargo and tanks loading, paper and steel industry, and financial management. An exponential computational time explosion can occur when solving multiple knapsack problems of actual industrial size using the dynamic programming method. Several branch and bound methods were proposed to solve this class of knapsack problems such as Ingargiola and Korsh (1975), Hung and Fisk (1978), Neebe and Dannenbring (1977), and Martello and Toth (1980).

Another variant of the 0-1 knapsack problem is the Multidimensional Knapsack Problem (MDKP) which is one of the extensively used integer programming problem. The problem has been heavily studied in capital budgeting and project selection after the work of Lorie and Savage (1955). Consider a knapsack of m number of constraints with capacities W_i. The problem can be formulated as follows:

$$\text{maximize} \quad \sum_{j=1}^{n} p_j \quad x_j$$

$$\text{subject to} \quad \sum_{j=1}^{n} w_{ij} \quad x_j \ \leq \ c_i \qquad 3.5$$

$$x_j \in \{0,1\}, \quad i = 1,\dots,m, \quad j = 1,\dots,n.$$

The problem is to select the n items or projects to maximize the total profit and meet the capacities of all the constraints. A set of m resources with capacities c_i are given. Each item j consumes an amount w_{ij} from each resource i. The 0-1 variable decides which items are selected.

A literature survey of the branch and bound and heuristics algorithms to solve this class of knapsack problems can be found in Freville (2004). The survey revealed that the bidimensional case showed limited success in finding exact solution with surrogate relaxations. Effective branch and bound solvers can provide exact solutions for small size instances of few hundreds variables once the number of constraints expands. Thus, heuristics remains a better choice when managing problems of three or more constraints.

This dissertation involves scheduling of large-scale petroleum development projects in a multiperiod planning horizon subject to a number of constraints. This problem can be best described by a generalization of the 0-1 knapsack problem which combines the multidimensional knapsack problem (MDKP) and the multiple knapsack problem (MKP). A general formulation of the Multidimensional Multiple Knapsack Problem (MDMKP) can be stated as follows:

$$\text{maximize} \quad \sum_{i=1}^{m} \ \sum_{j=1}^{n} p_{ij} \quad x_{ij}$$

$$\text{subject to} \quad \sum_{j=1}^{n} w_{ij} \quad x_{ij} \quad \leq \quad c_i$$

$$\sum_{i=1}^{m} x_{ij} \quad \leq \quad 1 \qquad 3.6$$

$$x_{ij} \in \{0,1\}, \quad i = 1, \ldots, m, \quad j = 1, \ldots, n.$$

This class of knapsack problems appeared lately to formulate models for a number of applications. Ang et al. (2007) proposed two heuristic algorithms to solve multidimensional multiple knapsack problem of large-scale. The optimization model was proposed to maximize profit of sea cargo over a multiperiod planning horizon. Lau and Lim (2006) used the multiperiod multidimensional knapsack problem to formulate logistics scheduling of e-Commerce ordering system, called Available-to-Promise. Tabu search and ant colony metaheuristic algorithms were proposed to solve the problem. Another similar problem is the resource allocation problem of maintenance and rehabilitation of highways networks. A multiperiod optimization model was proposed by Yoo (2004) to fund highway maintenance within a set of capital and maintenance and rehabilitation constraints. Dynamic programming and branch and bounds methods were combined to obtain an optimal or near-optimal solution. The author pointed that the model cannot be used to solve large-scale problems with expanded number of periods because the solution time grows exponentially beyond computational capability.

The following section will describe in detail the formulation of scheduling petroleum development and expansion projects to generate the maximum value across a multiperiod planning horizon without exceeding the various resources limits in any period.

2.4 Problem Formulation

The multidimensional multiple knapsack problem will be used to formulate and describe the problem of scheduling a set of projects or activities of known values and costs, subject to scarce resources, in a multiperiod planning horizon. The problem will be formulated as a binary integer program with an objective function in addition to a set of constrains and corporate guidelines or business rules. The objective is to improve the corporate economic performance by maximizing the aggregated NPV. Let i={1,2,…,T} be a set of integers representing T periods or knapsacks; Let j={0,1,2…,N} be a set of integers representing N projects of certain NPV in each period. The problem can be formulated as follows:

$$\text{Maximize} \quad \sum_{i=1}^{T} \sum_{j=1}^{N} NPV_{ij} \quad x_{ij} \qquad 3.7a$$

$$\text{subject to} \quad \sum_{i=1}^{T} \sum_{j=1}^{N} b_{ij} \quad z_{ij} \le B_i \qquad 3.7b$$

$$\sum_{i=1}^{T} \sum_{j=1}^{N} r_{ij} \quad z_{ij} \le R_i \qquad 3.7c$$

$$\sum_{i=1}^{T} \sum_{j=1}^{N} s_{ij} \quad z_{ij} \le S_i \qquad 3.7d$$

$$\sum_{i=1}^{T} \sum_{j=1}^{N} f_{ij} \quad z_{ij} \le F_i \qquad 3.7e$$

$$\sum_{i=1}^{T} \sum_{j=1}^{N} q_{ij} \quad z_{ij} \leq Q_i \qquad 3.7f$$

$$\sum_{i=1}^{T} \sum_{j=1}^{N} x_{ij} \quad \leq 1 \qquad 3.7g$$

$$\text{where} \quad x_{ij} = \begin{cases} 1 & \text{if project } j \text{ is selected in period i;} \\ 0 & \text{otherwise.} \end{cases}$$

The distribution of costs and value of a project are start-time dependent. The binary decision variable x_{ij} equals 1 if project j is selected in period i, and 0 otherwise. Eq. 3.7g represents inequality constraint which ensures that project j can be selected at most once. Another binary variable is z_{ij} which is an activation variable to set a project j active over the entire planning horizon if the project j is selected to start in year i. If i=4, then x_{ij} ={0,0,0,1,0,0,0,0,0,0} and z_{ij} ={0,0,0,1,1,1,1,1,1,1}. This assumption is practically acceptable since these projects typically require significant investment with extended project lifetime. The economic performance of each project is evaluated over 20-year period considering long-term commitment of very expensive investment. The business planning system of oil companies is typically based on five-year period. Large-scale petroleum projects may require from one to several years depending on development size, complexity of reservoirs, availability of resources, remoteness of the field, and hostility of field environment. The planning horizon in this study is defined by 10 periods. The motivating application includes years as the periods. The objective function in Eq. 3.7a maximizes the sum of NPV of selected projects over the 10-year planning horizon.

Large-scale petroleum development projects require a number of different resources. Adequate resources have to be allocated to meet project development requirements. The above formulation involves four resources constraints which are defined for all projects in all periods. The first constraint handles the limitations in yearly capital expenditures. A fixed amount of money is allocated for capital investment to develop new reservoirs or expand existing ones to improve economic performance and meet corporate goals. The required capital for a selected project j in year i is represented by b_{ij}. The available overall capital in year i is represented by B_i which may vary over the planning horizon (Eq. 3.7b). A large-scale petroleum development project requires significant amount of capital. The capital costs are incurred on drilling wells and installing new facilities. The base-year capital costs of each project are introduced to the model which escalates the costs according to the assigned year for project startup. The capital expenditures are distributed over the development stage which typically requires a number of years.

Eq. 3.7c represents inequality constraint characterizing the operating costs of each project and the operating budget limitations in each year over the planning horizon. A major element of the operating budget is the cost of manpower which imposes a challenge to the industry with current business expansions. The required operating cost in year i for project j is indicated by r_{ij}. The total allocated budget for operating costs in year i is indicated by R_i. This constraint should manage operating business requirements within an acceptable limit as the model seeks maximizing the financial value of available assets.

Inequality Eq. 3.7d and 3.7e are used to model the resources constraints associated with drilling rigs. Oil companies operate and contract a limited number of onshore and offshore rigs in planning period for the drilling and workover of wells. These resources constraints are represented in terms of rig-year. Eq. 3.7d states that the required onshore rig-year in period i for project j is s_{ij} and the total onshore rig-year available in that period is S_i. The variable s_{ij} encompasses the number of days required to move the rig and drill wells of project j in year i. Similarly, Eq. 3.7e states that the required offshore rig-year in period i for project j is f_{ij} and the total offshore rig-year available in that period is F_i.

Petroleum development projects are planned to produce at optimal levels. The startup of production requires a number of years to drill wells and install the required production system for large-scale projects. The optimal production levels are determined to enhance economic performance upon best management strategy to extract the oil from underground. However, the production rate may be restricted due to physical, technical, or strategic reasons. Production capacity is one example where production rate might be restricted from reaching optimal levels due to limitations in the production/injection system or number of wells. Furthermore, the production levels from reservoirs similar to those in the Middle East are planned based on moderate depletion rates to maximize recovery, reduce cost and extend reservoir plateau. Accelerated production, in the case of relaxed depletion rate policy, provides early revenue which may improve the project economics. However, substantial increases in depletion rate generally decrease the recovery of hydrocarbon from the reservoir. The strategy should allow increasing depletion rate to improve economic performance but bounded by technical limitations to prevent impact on recoverable reserves. The recovery is also related to the driving mechanisms of the reservoir which define production strategy. Reservoirs with gas cap expansion or water drive mechanisms are more susceptible to rate than dissolved gas expansion mechanism (Nystad 1985). Eq. 3.7f describes the production rate target or limitations where the overall production rate in period i is indicated by Q_i and the production rate from individual projects is indicated by q_{ij}.

Policy constraints can be utilized to impose assumptions, rules and guidelines. The followings are some examples (Startzman 2006).

- Select project 2 or project 3 but not both:

$$\sum_{i=1}^{T} x_{i2} + x_{i3} = 1$$

- Select both project 2 and project 3 or neither:

$$\sum_{i=1}^{T} x_{i2} - x_{i3} = 1$$

- If select project 3 then select project 2 but project 2 is still a candidate:

$$\sum_{i=1}^{T} x_{i2} - x_{i3} \geq 1$$

- Select both project 2 and project 3:

$$\sum_{i=1}^{T} x_{i2} + x_{i3} = 2$$

Interactions between projects are typical practice in the upstream sector of oil and gas industry. For instance, a number of neighboring fields are planned to share same processing facilities and cross-country pipeline. The model should account for the interdependencies among these projects.

CHAPTER III

OPTIMIZATION MODEL

The allocation of limited resources to investment projects in a company should be performed in a manner that maximizes the financial value of the assets. This requires an optimization model that computes the objective function and observes the limited resources. The purpose of this chapter is to present a new GA to solve an optimization problem in the area of petroleum development projects scheduling.

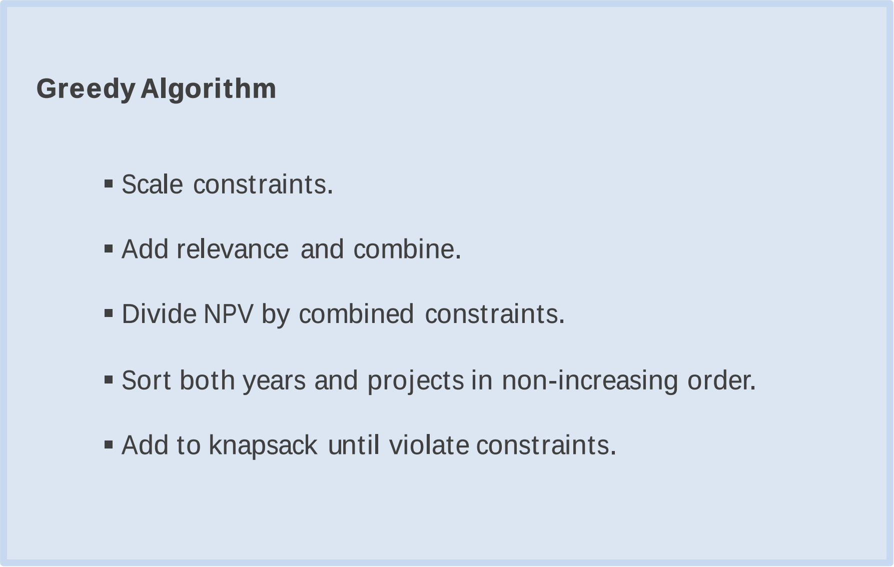
3.1 Construction Algorithm

An intuitive approach to solve the classical Knapsack Problems (KP), presented in the previous chapter, is to consider the profit to weight ratios of each item in the knapsack. The computed ratios, which are also called the efficiencies (e_{ij}), are sorted in non-increasing order. The idea of greedy algorithm is to add items from top to bottom into the knapsack if the capacity constraint is not violated. These items generate the highest profit while consuming the lowest amount when we deal with simple single constraint KP.

For Multidimensional Multiple Knapsack Problem (MDMKP), we can consider the same greedy construction algorithm as for simple KP with some modifications as explained by Kellerer et al. (2004). The efficiency value of each item will be the aggregation of all constraints. However, some constraints may dominate the ordering of the efficiency values due to the different order of magnitudes of the constraints. This can be resolved by scaling all the constraints inequalities. A relevance value (re) can be used to assign the proper weight to different constraints. The efficiency for a project j in period i can be defined as follow:

$$e_{ij} = \frac{NPV_{ij}}{re_B \frac{b_{ij}}{B_i} + re_R \frac{r_{ij}}{R_i} + re_S \frac{s_{ij}}{S_i} re_G \frac{f_{ij}}{F_i} + re_Q \frac{q_{ij}}{Q_i}} \qquad 3.1$$

A resource constraint will become less attractive as we increase the relevance value since the relevance value increases the scarcity of the corresponding resource. The algorithm procedure is shown in **Fig. 3.1**.



Greedy Algorithm

- Scale constraints.
- Add relevance and combine.
- Divide NPV by combined constraints.
- Sort both years and projects in non-increasing order.
- Add to knapsack until violate constraints.

Fig. 3.1—Construction algorithm for initial estimate.

3.2 Basic Elements of GA

A widely recognized metaheuristic method is the GA. This global search technique came as a result of the work of Holland (1975). The method is inspired by evolutionary biology, such as survival of the fittest, selection, mutation, and crossover. The GA method is simple, flexible and widely used for many practical problems, including scheduling and timetabling applications. It provides effective and efficient solutions for many problems that are too large and complicated to be solved by traditional methods.

The following description of the basic elements of the GA refers to Aarts and Lenstra (2003) and McCall (2005). The GA starts with chromosomes which are populated randomly in most cases. These chromosomes are string encodings of feasible solutions to a certain problem. Each position in the string represents a gene and the value occurring in that position represents an allele. A binary or non-binary bit strings can be used to encode solutions. Once the genetic population is defined, the fitness function is determined to distinguish between good and bad solutions. The fitness function is calculated by evaluating the chromosome quality of a particular solution.

A typical algorithm uses three genetic operators to evolve towards a better solution. The genetic operators are selection, crossover, and mutation. The selection process in the GA attempts to direct the population towards optimality in a manner similar to that of natural selection found in biological systems. This process uses the fitness function as evolution guide of chromosomes in a population. The chromosomes of higher fitness will have higher chance to be selected to build the reproducing set of population. The most common selection schemes are roulette wheel, tournament, and breeder selections.

The roulette wheel selection allocates probability to each chromosome proportional to its fitness (individual's fitness divided by sum of all chromosomes fitness). **Fig. 3.2** shows the roulette wheel selection of five individuals with fitness 10, 30, 25, 15 and 20. The tournament selection randomly picks pairs of chromosomes and selects the one with the best fitness. The breeder selection sort chromosomes based on their fitness in non-increasing order and select a certain fraction of top individuals.

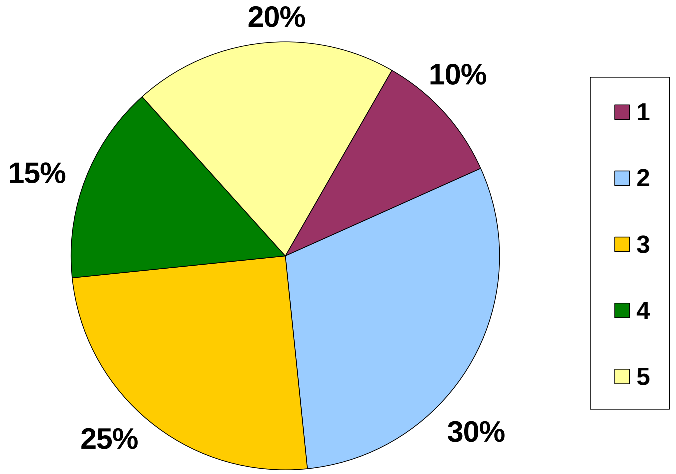


Fig. 3.2—Roulette wheel selection in the GA.

Recombination is the process of recombining selected chromosomes to produce new chromosomes. This process has two main components, the genetic operators crossover and mutation. The application of crossover and mutation produces new offspring. Mutation provides diversity while crossover improves local search. The crossover operator creates new offspring by combining the bits of two selected parent chromosomes. Many different forms of crossover can be used to improve local search. A single-point crossover is commonly used as shown in **Fig. 3.3**.

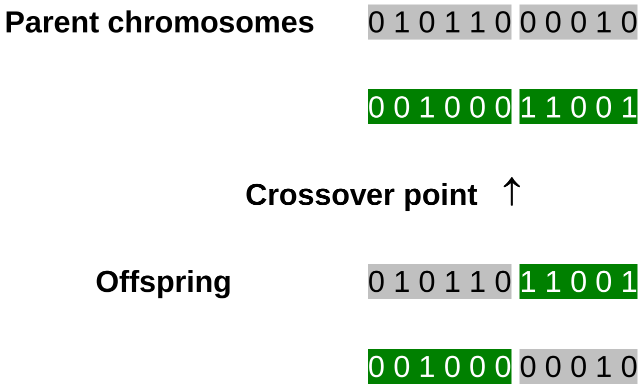


Fig. 3.3—Single-point crossover operator.

The single-point crossover occurs at position six. The first offspring populates bits in positions one to six from the first parent and positions seven to 10 from the second parent. Similarly, the second offspring populates bits in positions one to six from the second parent and positions seven to 10 from the first parent.

The mutation operator creates new chromosomes by flipping one or more bits value of individual chromosomes. This genetic operator is performed after the crossover to prevent solution from falling into local optimum. **Fig. 3.4** shows mutation operator occurring in the third bit by flipping the value from zero to one.

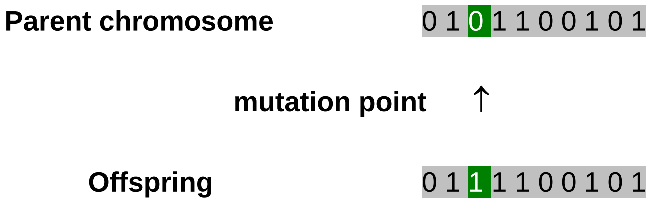


Fig. 3.4—Mutation operator.

GA is designed to produce good solutions to a wide range of practical problems. The design of a classical GA typically takes the fowling iterative process:

1. Generate initial population of chromosomes randomly.
2. Evaluate the fitness of all chromosomes in the population.
3. Select parent chromosomes and produce offspring by applying the genetic operators crossover and mutation.
4. Replace current population with the new one.
5. Stop if end condition is satisfied or return with best solution to step 2.

The development of a quality GA design for a given application requires modeling experience, problem knowledge and experimentation with different evolution schemes.

3.3 Implementation

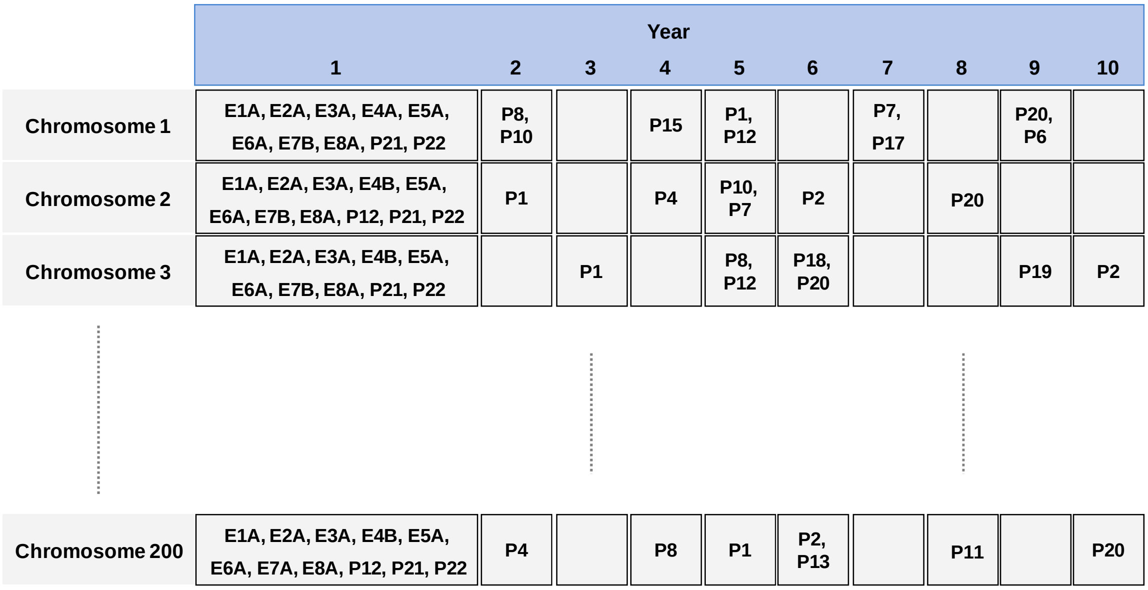
The GA has been successfully applied to a wide range of complex scheduling problems including the famous Traveling Salesman Problem (TSP). For instance, numerous GA were proposed to solve the Resource-Constrained Projects Scheduling Problem (RCPSP) (Valls et al. 2008; Debels and Vanhoucke 2007; Hartmann 1998; Leu and Yang 1999). The random nature of the GA expands the chances of finding a global solution. Experiments of various selection, crossover and mutation genetic operators have been attempted to improve the effectiveness of the model. The following is the final implementation of the algorithm.

3.3.1 Initial Population

A permutation based random search is used to generate an initial population of feasible solutions. First, a random fraction of every permutated projects sequence is selected and randomly spread over the planning horizon. This creates a chromosome which represents a schedule of selected projects. **Fig. 3.5a** shows projects schedules represented by chromosomes of non-binary encoding string of integers j, where j={0,1,2…,N} for N projects. **Fig. 3.5b** shows a binary encoding of individual chromosome 1 of Fig. 3.5a. The feasibility of generated chromosomes is evaluated observing all specified constraints throughout the planning horizon. A negative penalty value will be assigned to the fitness value which indicates that this solution is outside the feasible region. An initial population of 200 feasible chromosomes will be generated and arranged in non-increasing order.

3.3.2 Selection

After defining the initial population, the model selects parent chromosomes to construct new generations. The roulette wheel selection was first implemented. It was replaced later with the breeder selection to improve the model performance. In breeder selection, the chromosomes are arranged in descending order according to their fitness. A specified segment of the best chromosomes (200 chromosomes) is selected producing highly fit solutions.



	Year									
	1	2	3	4	5	6	7	8	9	10
Chromosome 1	E1A, E2A, E3A, E4A, E5A, E6A, E7B, E8A, P21, P22	P8, P10		P15	P1, P12		P7, P17		P20, P6	
Chromosome 2	E1A, E2A, E3A, E4B, E5A, E6A, E7B, E8A, P12, P21, P22	P1		P4	P10, P7	P2		P20		
Chromosome 3	E1A, E2A, E3A, E4B, E5A, E6A, E7B, E8A, P21, P22		P1		P8, P12	P18, P20			P19	P2
⋮			⋮					⋮		
Chromosome 200	E1A, E2A, E3A, E4B, E5A, E6A, E7A, E8A, P12, P21, P22	P4		P8	P1	P2, P13		P11		P20

Fig. 3.5a—An initial population of 200 feasible schedules (chromosomes).

3.3.3 Crossover and Mutation

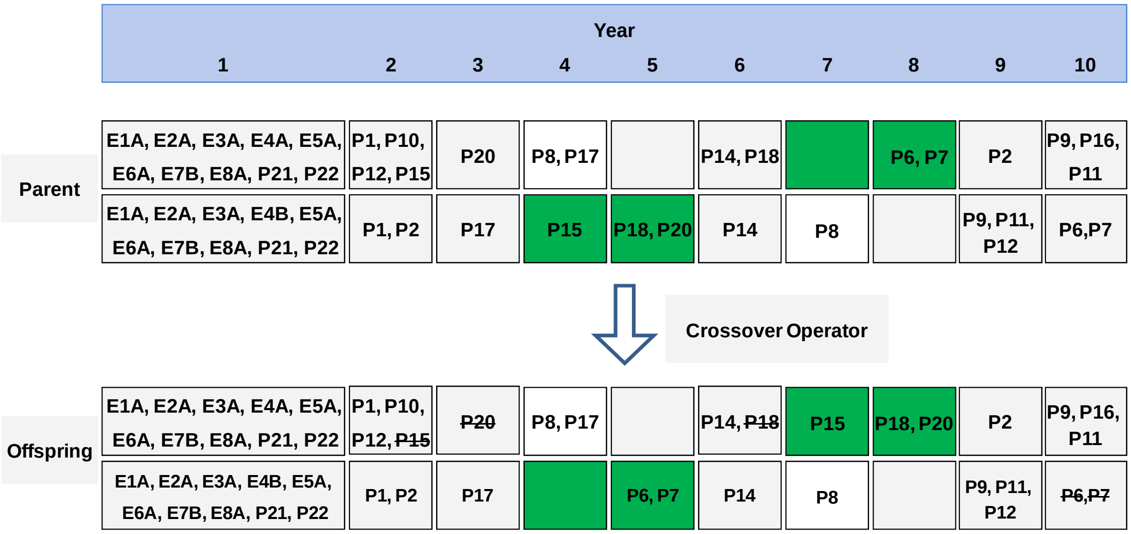
The model applies genetic operators to selected chromosomes to evolve towards better solution. The choice of genetic operators is crucial for the success of the algorithm. This is generally identified on the basis of computational experiments.

First, two parent chromosomes are selected for single-point crossover operator. The chromosomes of the couples are selected from the fittest individuals in descending order. The offspring will be produced from performing the crossover in a random manner across one to three years. The points of crossover of the parent chromosomes are randomly drawn from the 10-year planning horizon. The model verifies the assumption that each project can be executed only once while performing the crossover. An illustration of the single-point crossover is shown in **Fig. 3.6**.

	Year									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
P1	0	0	0	0	1	0	0	0	0	0
P2	0	0	0	0	0	0	0	0	0	0
P3	0	0	0	0	0	0	0	0	0	0
P4	0	0	0	0	0	0	0	0	0	0
P5	0	0	0	0	0	0	0	0	0	0
P6	0	0	0	0	0	0	0	0	1	0
P7	0	0	0	0	0	0	1	0	0	0
P8	0	1	0	0	0	0	0	0	0	0
P9	0	0	0	0	0	0	0	0	0	0
P10	0	1	0	0	0	0	0	0	0	0
P11	0	0	0	0	0	0	0	0	0	0
P12	0	0	0	0	1	0	0	0	0	0
P13	0	0	0	0	0	0	0	0	0	0
P14	0	0	0	0	0	0	0	0	0	0
P15	0	0	0	1	0	0	0	0	0	0
P16	0	0	0	0	0	0	0	0	0	0
P17	0	0	0	0	0	0	1	0	0	0
P18	0	0	0	0	0	0	0	0	0	0
P19	0	0	0	0	0	0	0	0	0	0
P20	0	0	0	0	0	0	0	0	1	0
P21	1	0	0	0	0	0	0	0	0	0
P22	1	0	0	0	0	0	0	0	0	0
E1A	1	0	0	0	0	0	0	0	0	0
E1B	0	0	0	0	0	0	0	0	0	0
E2A	1	0	0	0	0	0	0	0	0	0
E2B	0	0	0	0	0	0	0	0	0	0
E3A	1	0	0	0	0	0	0	0	0	0
E3B	0	0	0	0	0	0	0	0	0	0
E4A	1	0	0	0	0	0	0	0	0	0
E4B	0	0	0	0	0	0	0	0	0	0
E5A	1	0	0	0	0	0	0	0	0	0
E5B	0	0	0	0	0	0	0	0	0	0
E6A	1	0	0	0	0	0	0	0	0	0
E6B	0	0	0	0	0	0	0	0	0	0
E7A	0	0	0	0	0	0	0	0	0	0
E7B	1	0	0	0	0	0	0	0	0	0
E8A	1	0	0	0	0	0	0	0	0	0
E8B	0	0	0	0	0	0	0	0	0	0

Fig. 3.5b—Genetic coding representation of chromosome 1 using binary bit vectors.

The mutation operator is implemented as a second genetic operator to create new individuals from parent chromosomes with projects sequence that could not be created through crossover operator. The proposed model randomly draws one to two consecutive years of parent chromosomes for mutation operator. The projects in the drawn years will be randomly moved either one year before, one year after or remain in the same year. A schematic of the mutation operator is shown in **Fig. 3.7**. This genetic operator allows exploring the entire search space and avoids falling in local optimum.



Year	1	2	3	4	5	6	7	8	9	10
Parent	E1A, E2A, E3A, E4A, E5A, E6A, E7B, E8A, P21, P22	P1, P10, P12, P15	P20	P8, P17		P14, P18	🟩	P6, P7	P2	P9, P16, P11
	E1A, E2A, E3A, E4B, E5A, E6A, E7B, E8A, P21, P22	P1, P2	P17	P15	P18, P20	P14	P8		P9, P11, P12	P6,P7
Offspring	E1A, E2A, E3A, E4A, E5A, E6A, E7B, E8A, P21, P22	P1, P10, P12, ~~P15~~	~~P20~~	P8, P17		P14, ~~P18~~	P15	P18, P20	P2	P9, P16, P11
	E1A, E2A, E3A, E4B, E5A, E6A, E7B, E8A, P21, P22	P1, P2	P17	🟩	P6, P7	P14	P8		P9, P11, P12	~~P6,P7~~

Fig. 3.6—Implementation of single-point crossover operator.

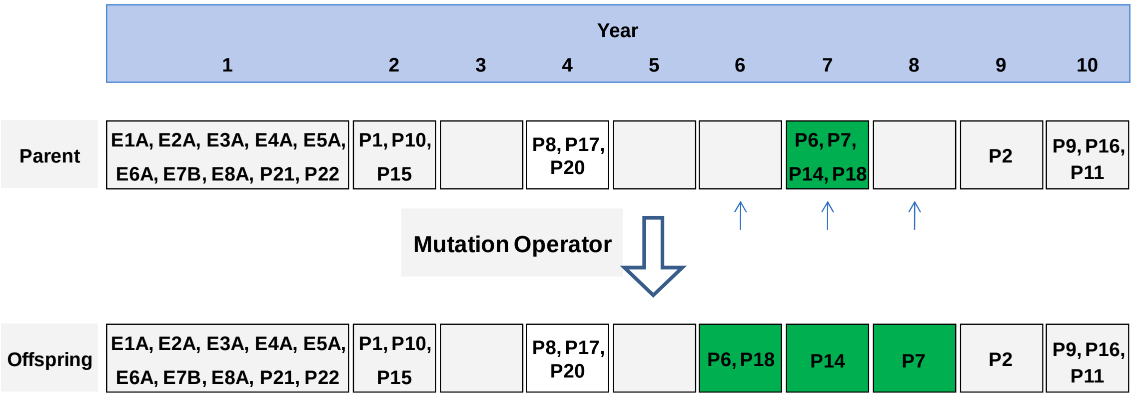


Fig. 3.7—Implementation of mutation operator.

3.3.4 Individuals and Fitness

A pre-specified percentage of the top fitness values will be selected for new genetic operations (crossover and mutation). Solutions outside the feasible region will be removed from the population. A penalty function is used to penalize unfeasible solutions. The sum of violations c_k for a schedule k can be defined by the following penalty function:

$$c_k = \sum_{z=1}^{Z} \sum_{i=1}^{T} \sum_{j=1}^{N} \delta_{ijzk} \qquad 3.2$$

$$\text{where} \quad \delta_{ijzk} = \begin{cases} 0 & \text{if a constraint is satisfied;} \\ -100 & \text{otherwise.} \end{cases}$$

where z is the number of resources constraints.

A predefined loop is set in search for improving the fitness value of the new offspring while observing the sets of predefined constraints along the planning horizon. A lower bound was implemented in the algorithm to reduce search space. The algorithm improves the lower bound value from one generation to another as the solution evolves towards optimality. **Fig. 3.8** shows the proposed algorithm architecture to solve the scheduling problem of large-scale petroleum development and expansion projects in multiperiod planning horizon. **Fig. 3.9** shows a schematic of the algorithm.

```
Step 1,
    ▪ $K = 1$
    ▪ Create permutation based initial population.
Step 2,
    ▪ Create new projects schedules by mating individuals in the current population using crossover and mutation.
    ▪ Evaluate new members.
    ▪ Sort schedules in descending order based on their fitness and keep highly fit members (breeder selection).
    ▪ Set lower bound.
Step 3,
    ▪ $K = k + 1$
    ▪ If stopping condition = true then return the best individuals as the solution and stop.
    ▪ Else go to step 2.
```

Fig. 3.8—Architecture of genetic algorithm.

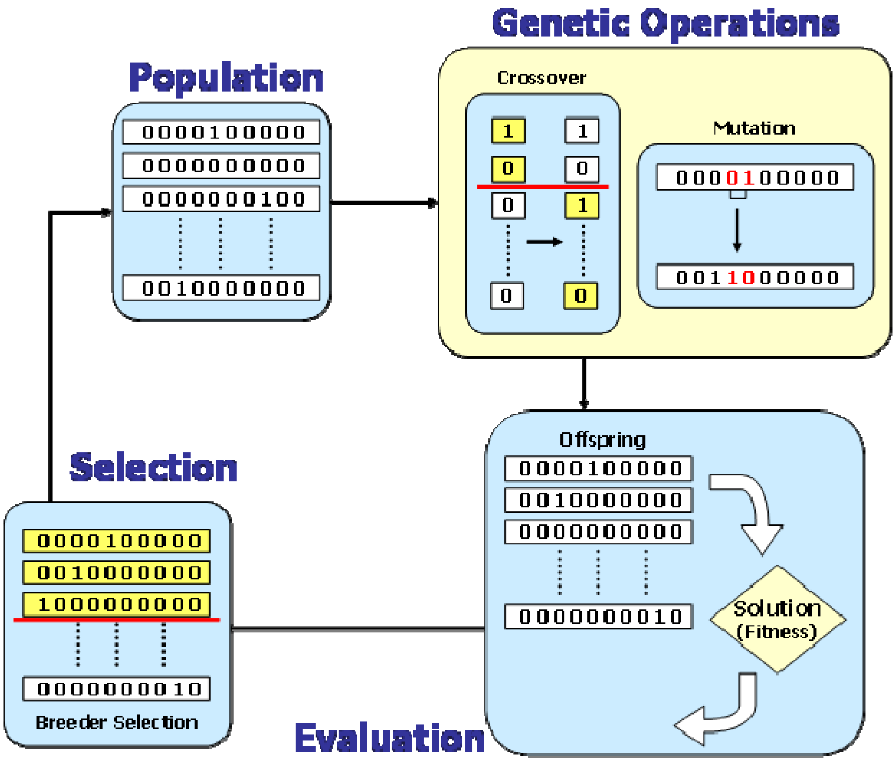


Fig. 3.9—A schematic of genetic algorithm.

CHAPTER IV

PETROLEUM PROJECTS

Oil and gas are projected to continue leading the energy market in meeting the world's growing energy demand for the foreseeable future. The projection of world consumption of oil is set to expand from the 2005 level of 83 million B/D to reach 118 million B/D by 2030 (Annual Energy Outlook 2007 (AEO2007) by EIA). The projected levels require large number of investments in petroleum development projects. The expansion of production capacity is essential in meeting increasing demand to insure stability of supply and security of market.

4.1 Characteristics of Oil and Gas Projects

Petroleum projects involve various stages from exploration in the beginning to abandonment when reaching the economic limit as shown in **Fig. 4.1**. This work is concerned with development projects of undeveloped-proved reserves and expansion projects of developed-proved reserves. The model evaluates large-scale petroleum projects characterized by moderate to low depletion rate. The constrained depletion strategy prolongs the production plateau life of the project, provides long-term profit and stabilities, and maximizes ultimate recovery. Furthermore, the moderate to low depletion strategy helps harmonizing production supply with OPEC's policy.

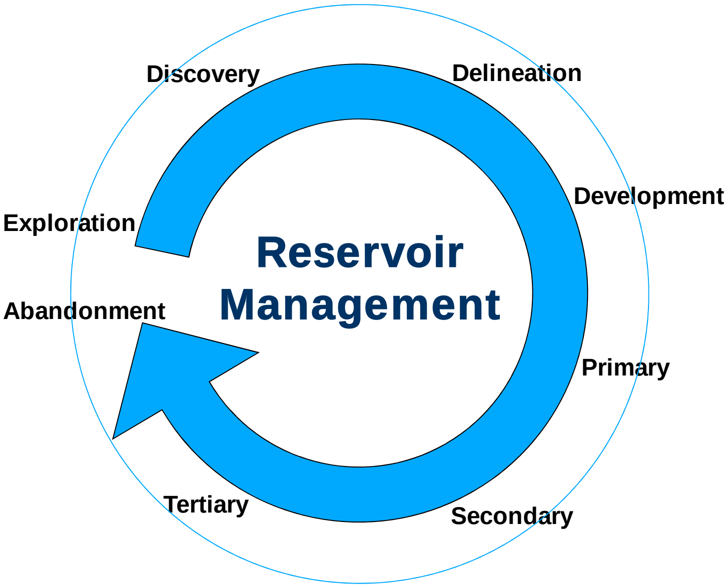


Fig. 4.1—Stages of petroleum projects.

The lifecycle of a typical large-scale petroleum project of constrained depletion rate strategy extends many decades from its startup to abandonment. The economic performance of each project will be evaluated over 20-year period from the long project lifecycle. The proposed model employs a general objective function that maximizes NPV by selection and scheduling of the investments projects over 10-year planning horizon under well-defined constraints. An average production rate is assumed in each period. This is a valid assumption since the concerned projects are produced at constrained depletion rate which prolong production plateau life as shown in **Fig. 4.2**. Large-scale petroleum projects will be defined as projects of proved reserves of several hundred million barrels. The development phase involves various design, drilling, and construction activities before production startup. The completion of these activities typically requires a number of years. The duration may become significant when the development involves large-scale projects, complex reservoirs and hostile terrains. The study assumes a development phase of two years for onshore projects and three to four years for offshore projects.

The proposed model will address deterministic data. An extension of the current model would be required to account for different classes of reserves. Further uncertainties such as market prices can also be incorporated to provide thorough risk assessment.

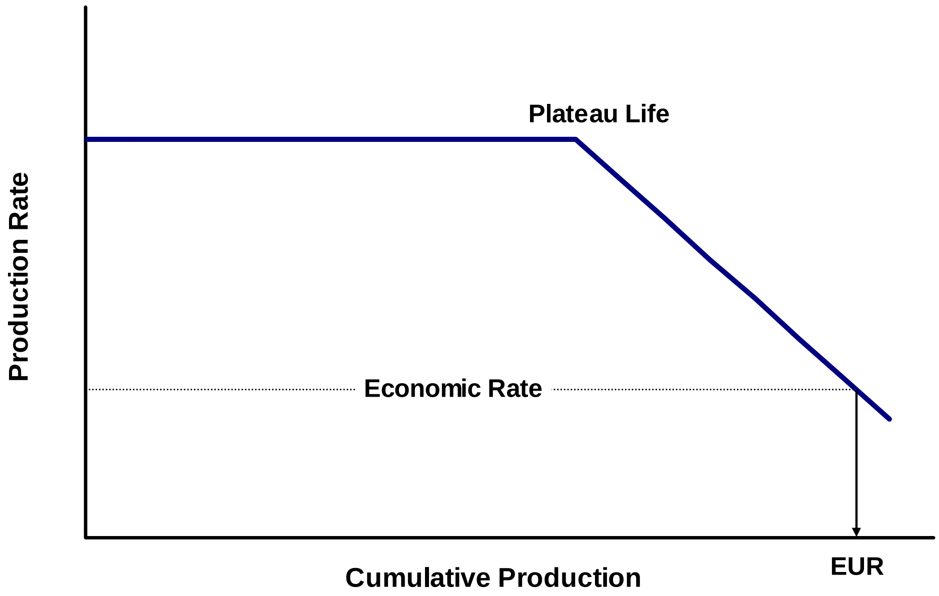


Fig. 4.2—Decline curve of an oil reservoir.

4.2 Oil Markets

The history of oil market has shown significant volatility in oil prices. The volatility is expected to increase in the long-term which requires assessment of wide range of price cases. **Fig. 4.3**, from AEO2007 by EIA, depicts three price cases: reference, high, and low prices. The reference case projects slight variation in world oil prices from 2005 levels to 59 USD per barrel in 2030. The price paths in the high and low cases depict wide fluctuation varying from USD 36 per barrel to USD 100 per barrel in 2030. Various assumptions and issues are used to build the three price paths. The role of OPEC and its longstanding commitment is the most crucial issue to the oil market stability in the long-term.

The EIA prices forecasts are apparently far below the market actual prices. The proposed model will employ the EIA forecasts for illustrative purposes. The three price paths will be used to assess the model performance under prices fluctuations. The model will manage oil and gas of various qualities of different crude markets. Thus, the model will use price differentials to account for the products values of various projects in the markets. A complete projection of the oil prices of different projects based on the three world oil price cases is included in Appendix-A.

4.3 Petroleum Field Development Study

A study of petroleum field development project involves various technical tasks and resources to perform these tasks. A multidisciplinary team performs the tasks from different E&P disciplines of geophysics, geology, petrophysics and petroleum engineering.

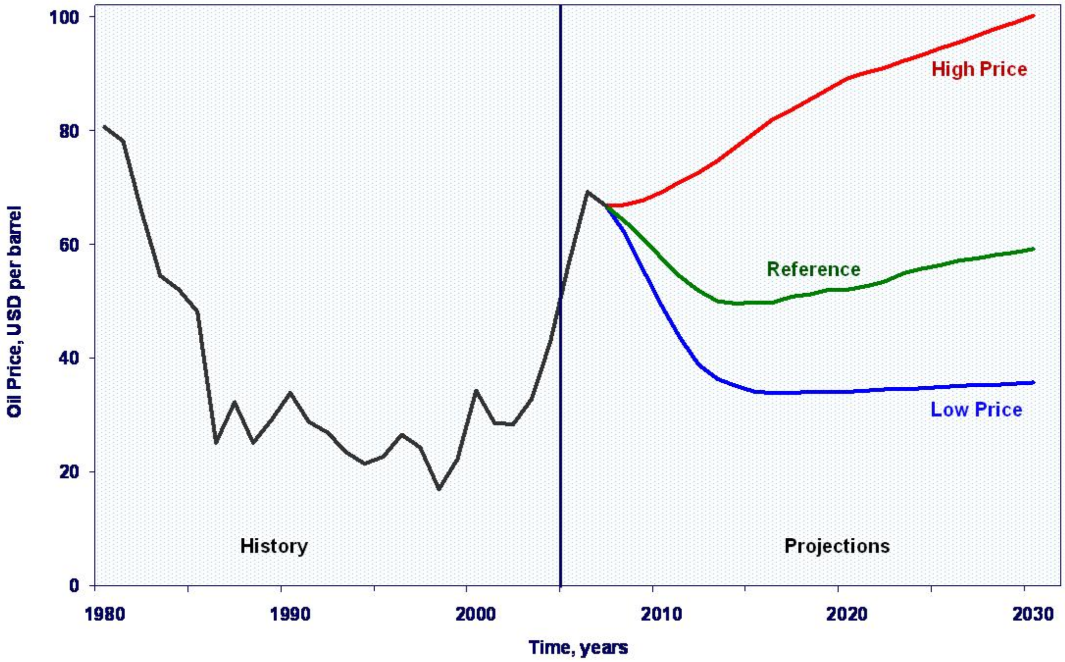


Fig. 4.3—World oil prices from EIA, AEO2007.

A geological model has a significant impact on the results of a reservoir study. The geological model requires a number of workflow stages which involves structural, stratigraphic, fracture and lithological models. Detailed numerical reservoir simulation model has become a standard tool in developing and managing hydrocarbon reservoirs. The reservoir simulation model provides hydrocarbon production forecast which enables cash flow projection. The tool offers the flexibility to study the reservoir and provide the required forecast under various production strategies and wells spacing and patterns. It also provides solutions to complex reservoirs problems which could not be solved by analytical methods. The complexity arises from the heterogeneity and structure geometry of the reservoirs and the nonlinearity of fluid flow through rocks and production system. A significant part of any simulation study is the history matching which is the process of validating the model. This is achieved by modifying the input data to improve the match between actual historical production data and past reservoir performance from simulation runs. Critical aspects of the history match are the non-uniqueness and iterative nature of the process (Mattax and Dalton 1990). The history matching process attempts to reproduce historical production and injection rates, and pressures on field and wells levels.

The challenge is to properly integrate all the tasks in a consistent model and apply optimization methods to maximize the economic performance of the field. Several models were proposed to solve the problem as discussed in the literature review section. This work will not involve field development studies of individual projects. The results of these studies are assumed to be available.

4.4 Economic Model

Independent economic evaluation of multiple development projects does not ensure optimal results in the presence of resources limitations. The evaluation should maximize the NPV of projects cash flow streams in the aggregate by best selection of investments from a large number of opportunities as described in **Fig. 4.4**. The best selection can be accomplished through proper application of optimization methods.

The cash flow of a project option involves several streams of sales revenue and incurred costs. The revenue comes from selling of oil and gas volumes at projected prices. The costs incur from development costs, operation and maintenance expenses, and future infill drilling programs. The costs of development projects for oil and gas have escalated in recent years. Future trends of the development costs are difficult to determine. The analysis assumes a continuation of current trend. The development costs involve various activities: design, construction, installation of production facilities along with onshore and offshore drilling.

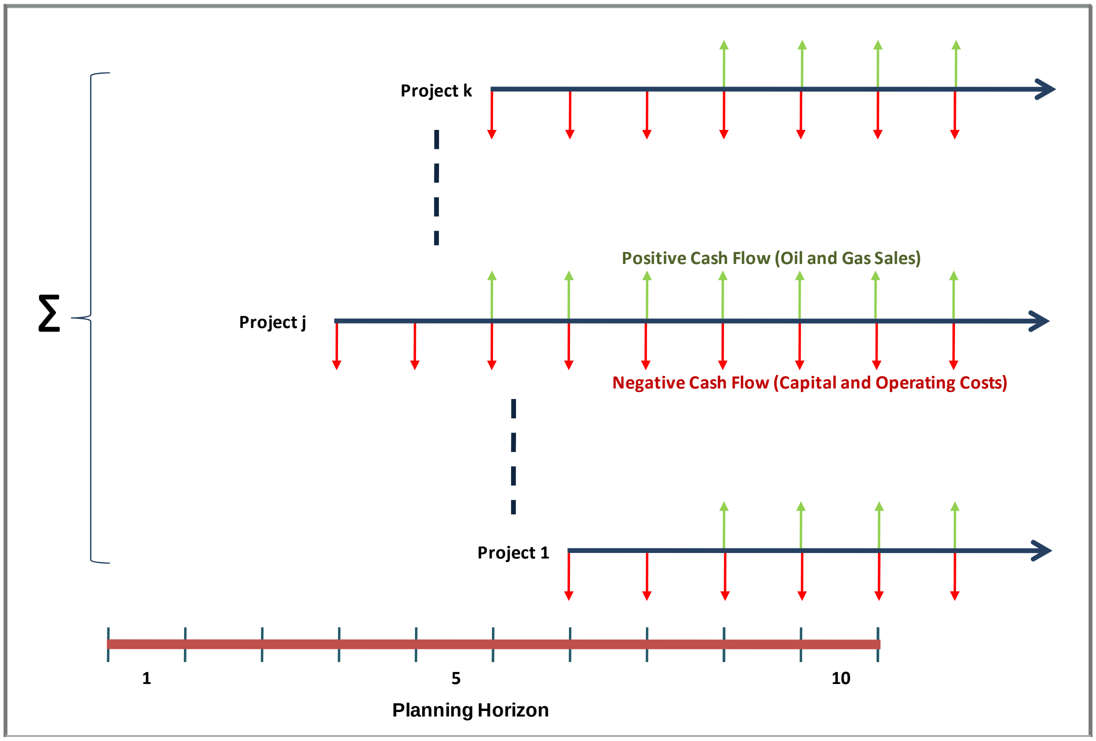


Fig. 4.4—Cash flow streams in the aggregate.

The NPV is determined by discounting the cash flows at 10% over the 20-year evaluation period. The model uses estimates of the yearly escalation rates for the various activities as follows:

Facilities and Drilling Costs	3.0%
Operation Costs	3.25%

Capital costs of E&P upstream development projects consist of those from installation of production facilities and developmental drilling. The facilities may include upstream infrastructure, pipelines, platforms, vessels, pumps, compressors and other upstream processing equipment. The developmental drilling may include producers, injectors and water supply wells.

Operation costs include a defined fixed component and a variable fraction. The fixed component is defined based on an annual percentage of the initial investment in production facilities. The variable is determined from allocating a percentage or a fraction of the produced volume and the wells that requires workover, services (tests, wirelines, logs...etc) and artificial lift equipment.

The model assumes that all projects are irreversible and indivisible. The development decision in the E&P upstream projects requires significant amount of irreversible investment which may reach several billions of dollars. The projects are defined as indivisible opportunities which are either developed or not.

The cost streams of drilling, facilities and operation costs are assumed to be available to the model in base year dollar. The model will escalate the costs according to the selected year. The fiscal system and tax model are area-specific and will not be included in the analysis.

4.5 Proposed Development and Expansion Projects

Petroleum development projects require considerable amount of investments and technical efforts. In this section, the results of oil field development and expansion studies are shown by streams of incurred capital and operating costs, production rates and drilling requirements. Although economic evaluation may favor higher levels of production, the study adheres to petroleum development projects of constrained depletion. The evaluation includes development of moderate depletion rates to maximize recovery, reduce cost and extend reservoir plateau. Furthermore, the maximum depletion may not generate the maximum value due to constraints and availability of undeveloped projects of high economic potential.

In this section, development projects of 22 new fields and expansion projects of 8 existing fields are presented to illustrate the performance of the algorithm. The 30 projects are used for illustrative purposes and do not reflect any real data. The figures include the rig-year of onshore and offshore drilling requirements, and the production rates of oil and gas. They also include the yearly costs of drilling, facilities, and operations. All the cost parameters are specified in base-year dollar of 2008 and the model will escalate them to corresponding years. A 20-year evaluation period is assumed with 20 periods, each of a length of one year.

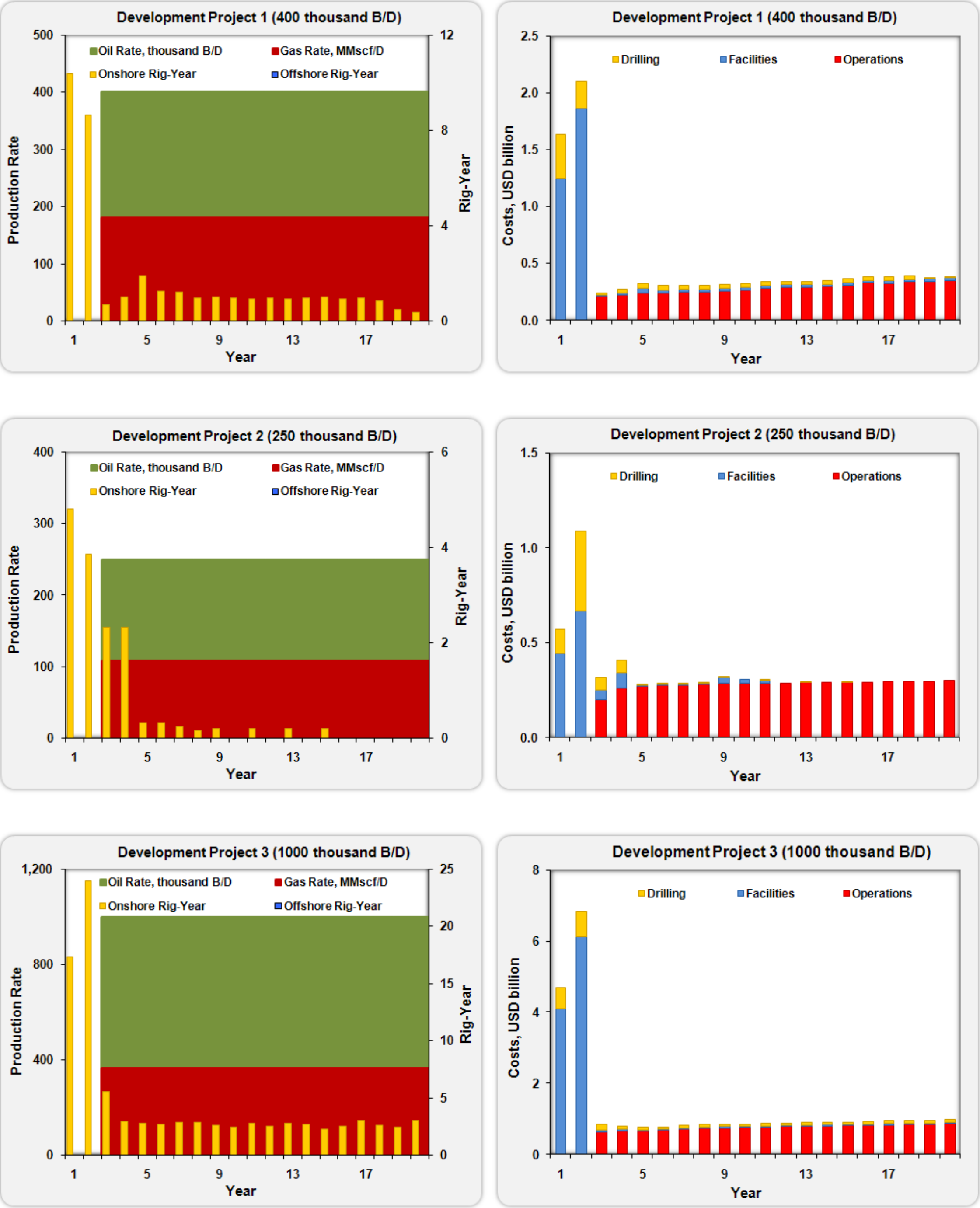


Fig. 4.5a—Development projects P1 to P3.

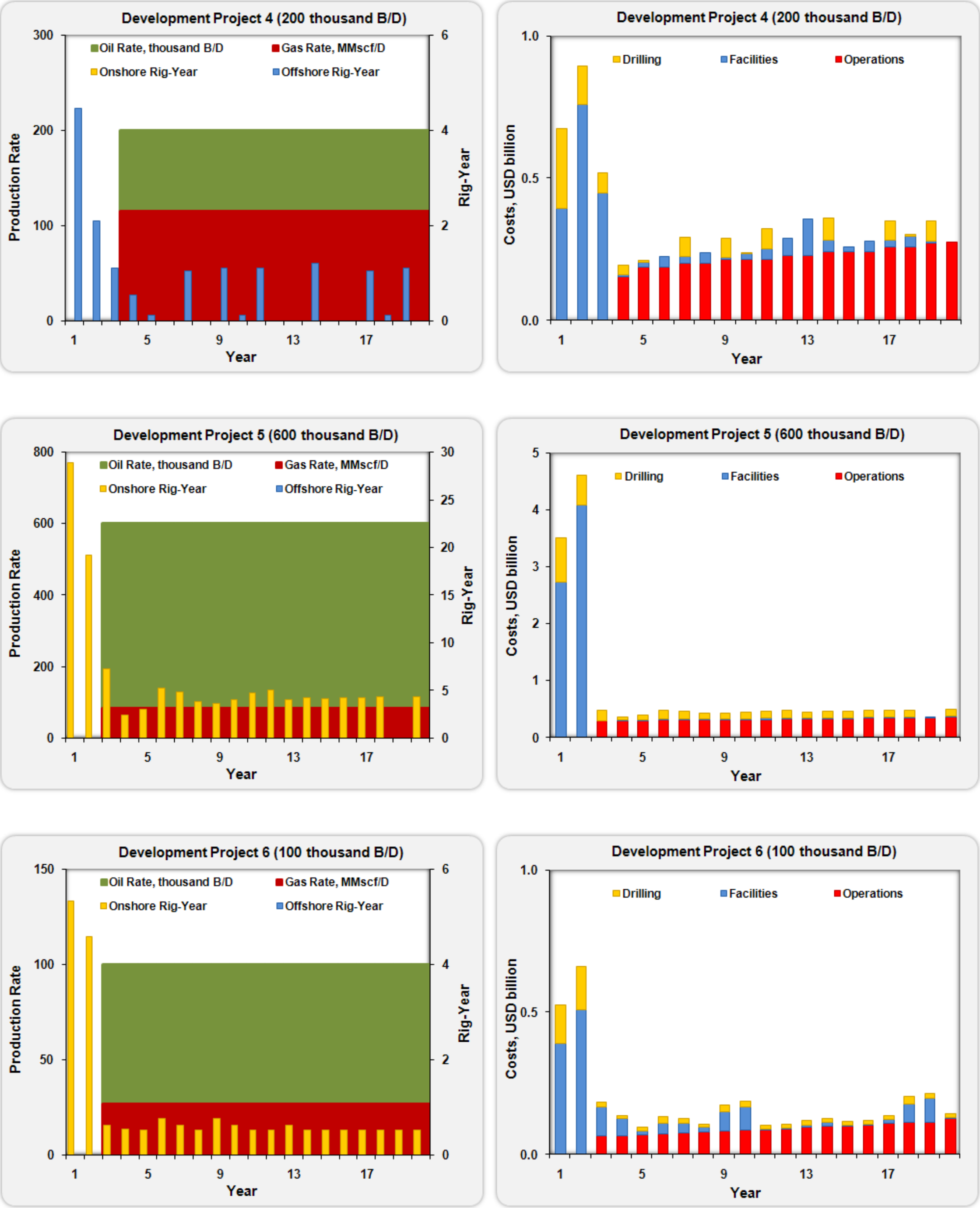


Fig. 4.5b—Development projects P4 to P6.

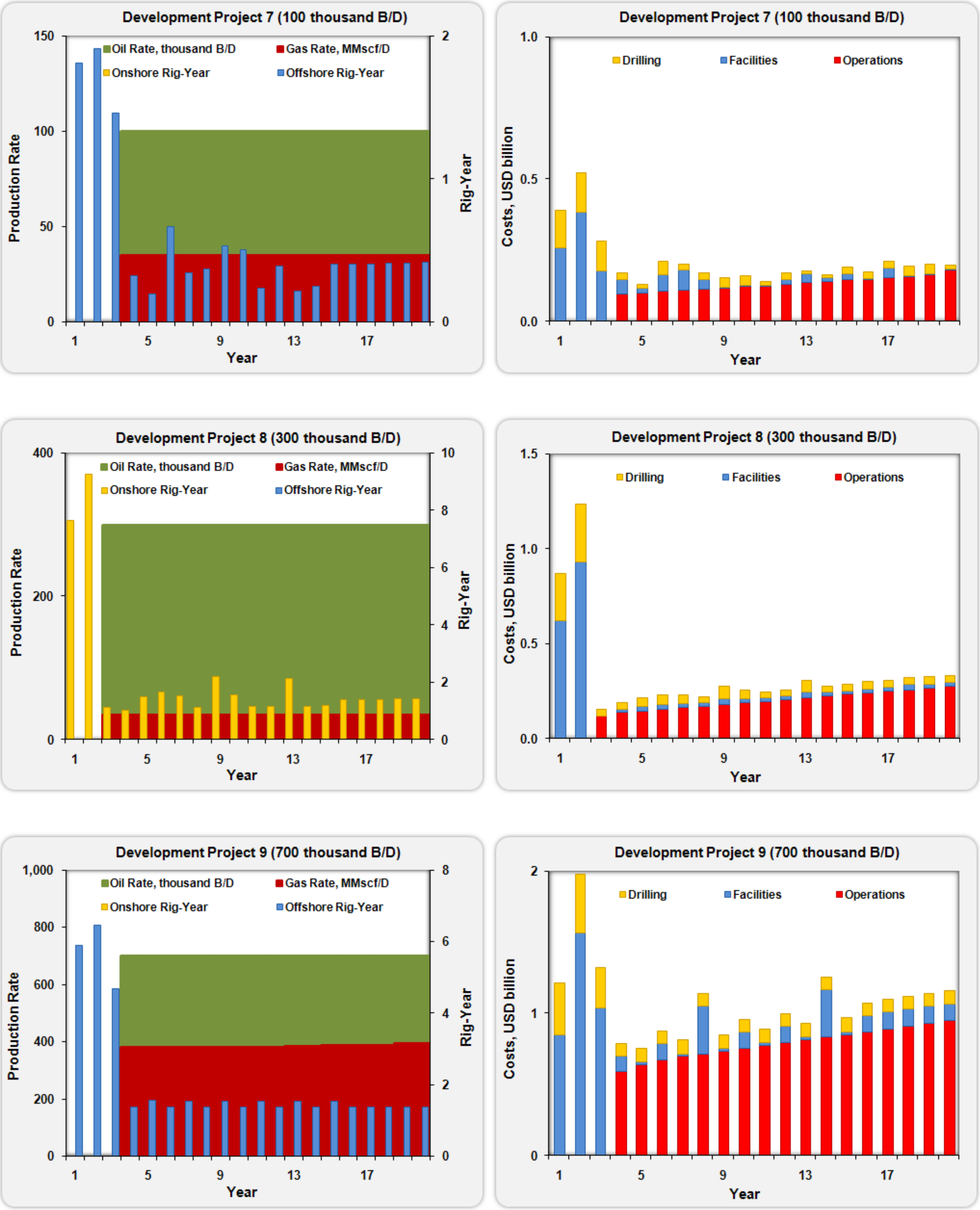


Fig. 4.5c—Development projects P7 to P9.

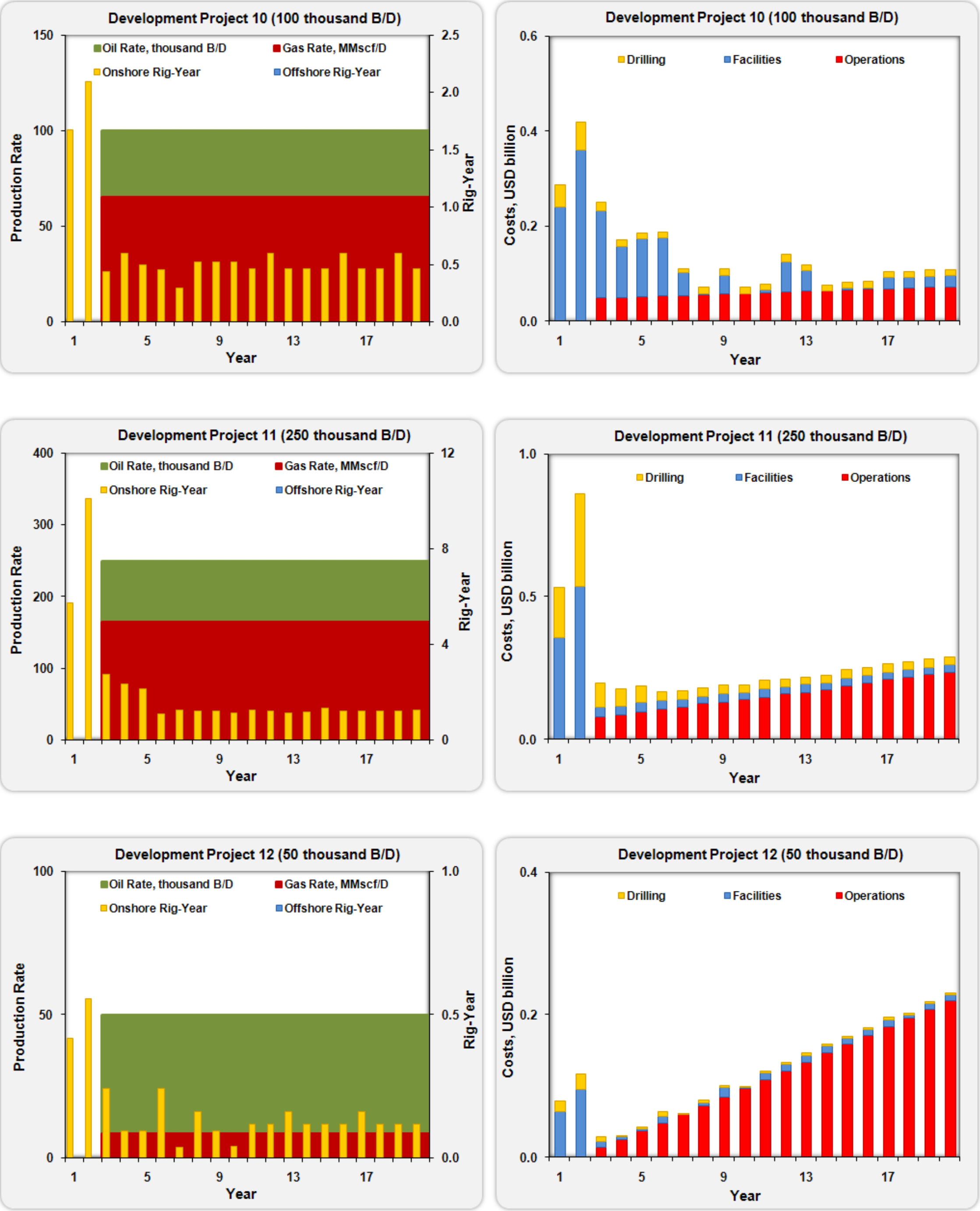


Fig. 4.5d—Development projects P10 to P12.

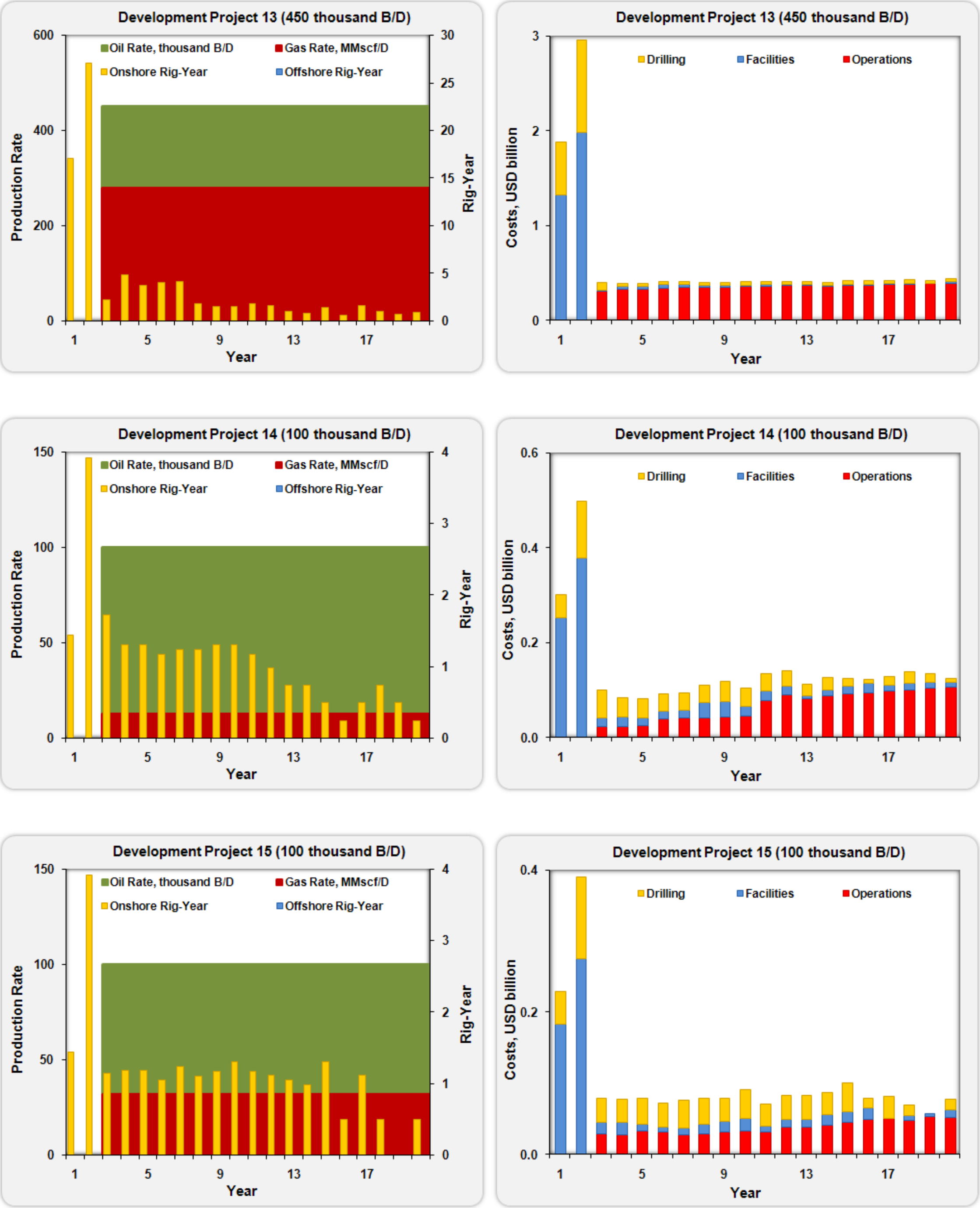


Fig. 4.5e—Development projects P13 to P15.

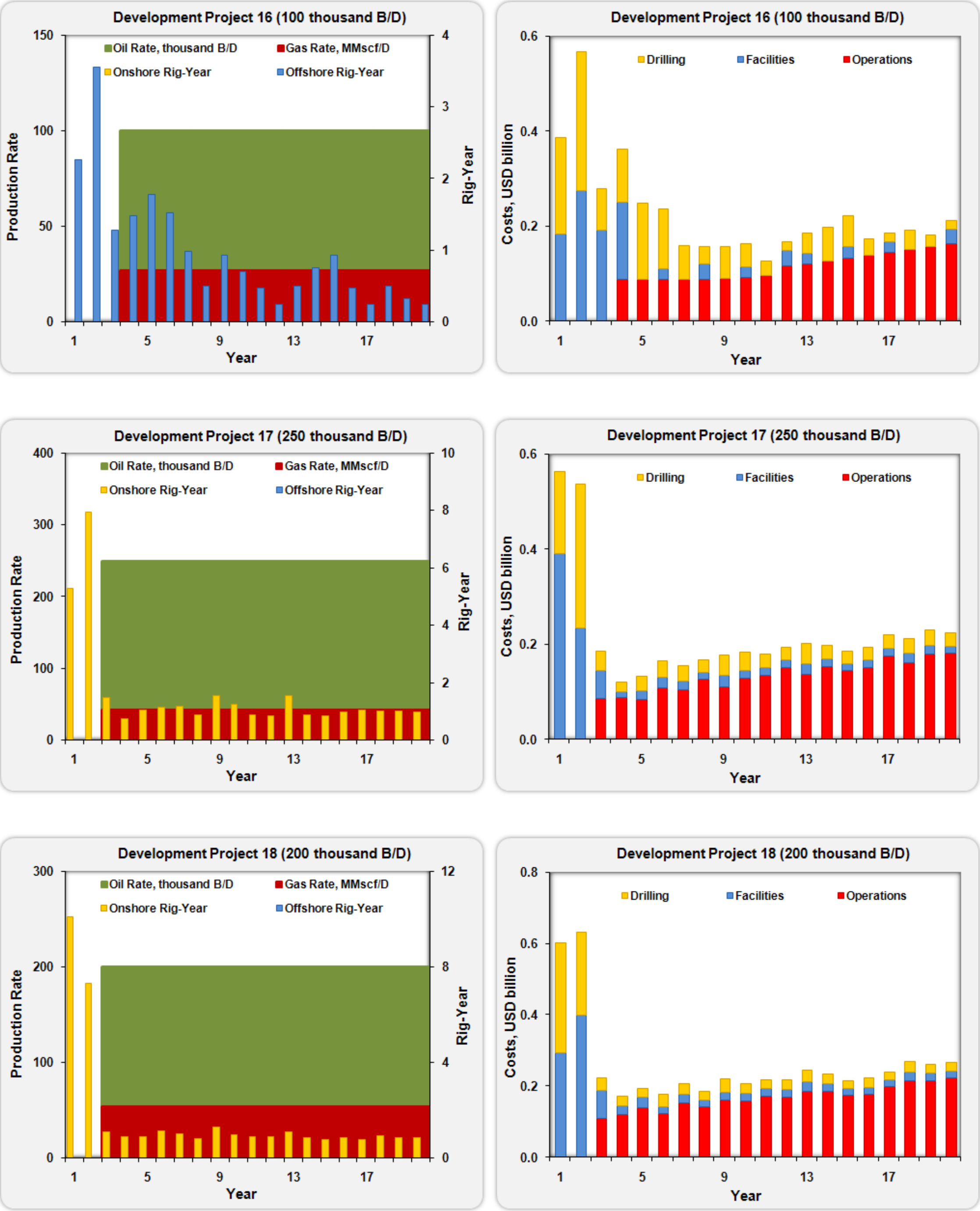
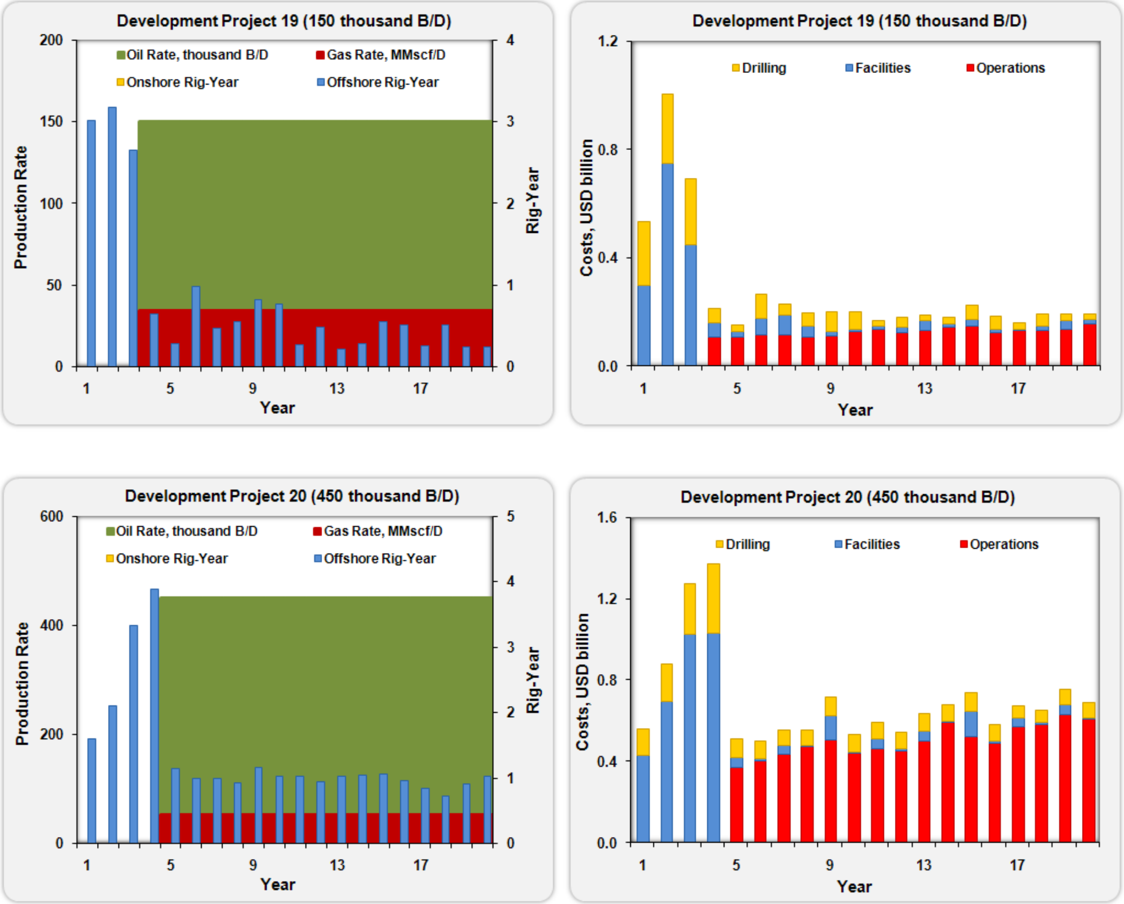


Fig. 4.5f—Development projects P16 to P18.


Development Project 19 (150 thousand B/D)

Development Project 19 (150 thousand B/D)

Development Project 20 (450 thousand B/D)

Development Project 20 (450 thousand B/D)

Fig. 4.5g—Development projects P19 and P20.

The 22 development projects are illustrated in **Figs. 4.5a through 4.5h**. For instance, project P1 presents an onshore oil field development with oil production rate of 400 thousand B/D and associated gas production rate of 180 MMscf/D. The project requires two years of development stage to drill the wells and install the required production facilities. The development drilling requires 10.4 and 8.6 rig-year in year one and two, consecutively. This initial drilling would cost USD 633 million. The required capital for development facilities is estimated at USD 3.1 billion. The operating cost in the first year of production (year three) is estimated at USD 207 million.

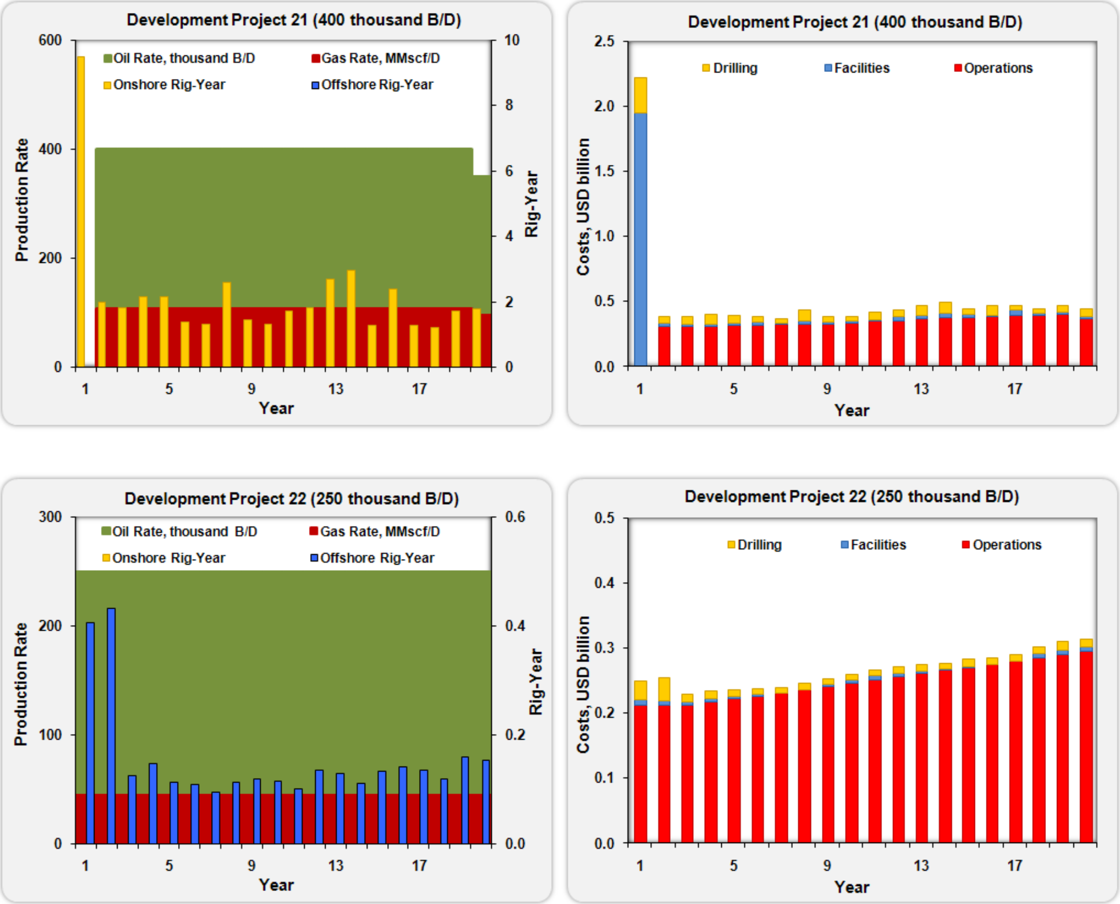


Fig. 4.5h—Development projects P21 and P22.

Projects P21 and P22 (Fig. 4.5h) are in the development stage. The projects should remain active over the entire planning horizon since investments are irreversible.

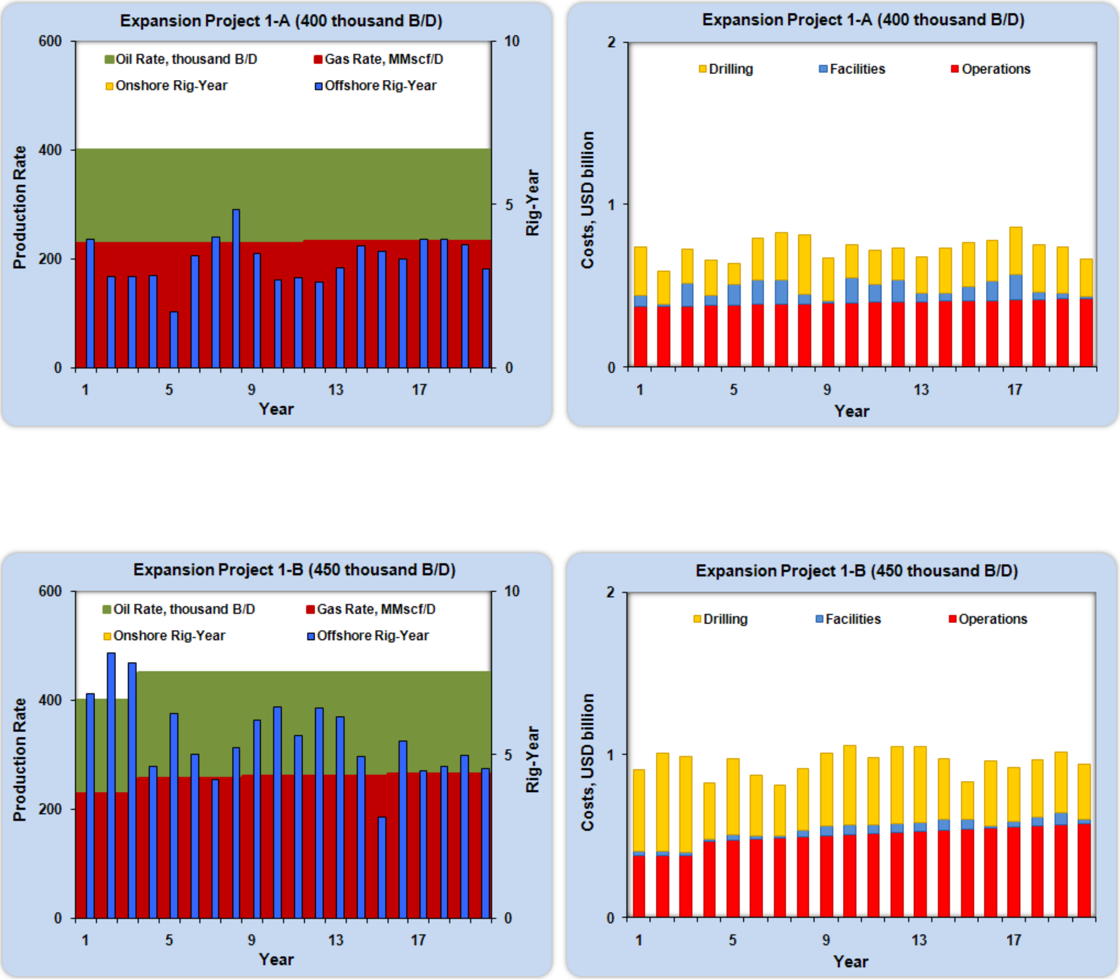


Fig. 4.6a—Expansion project E1.

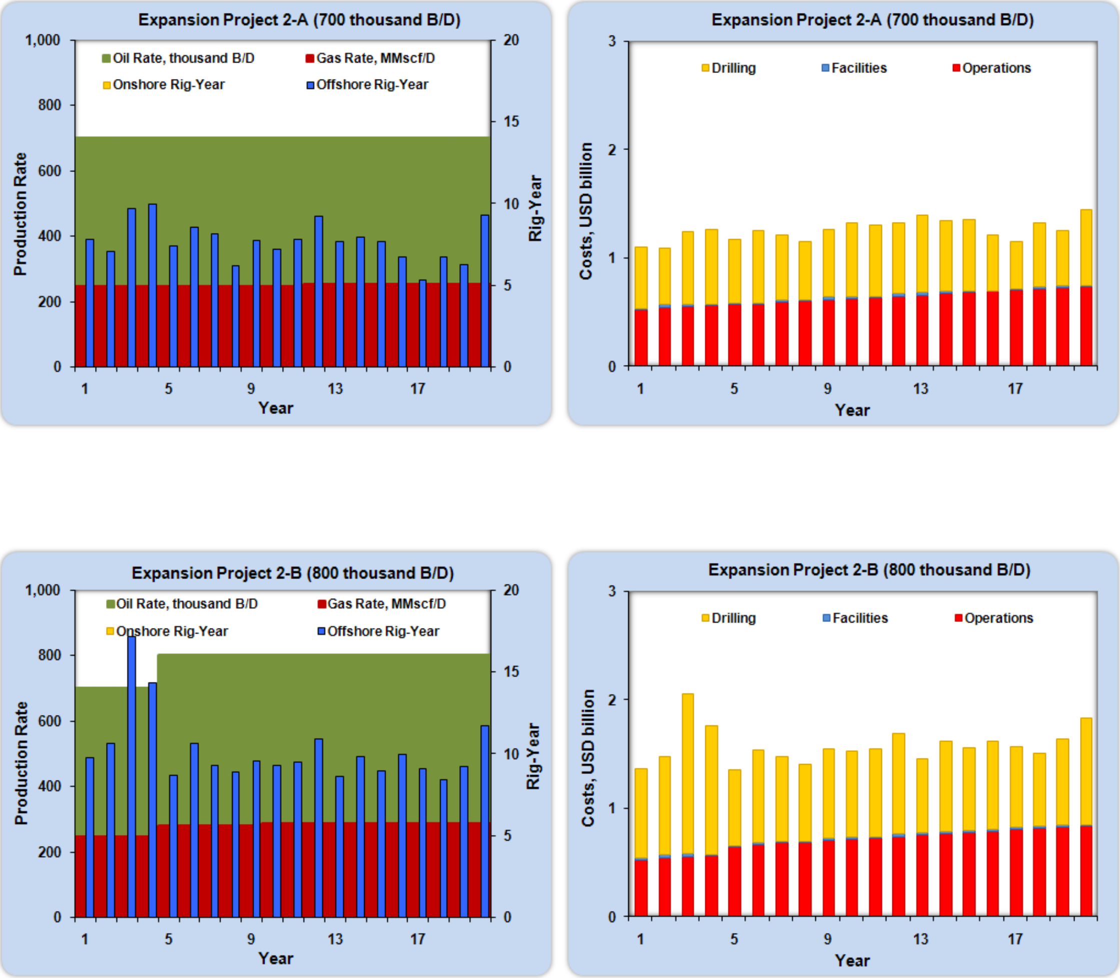


Fig. 4.6b—Expansion project E2.

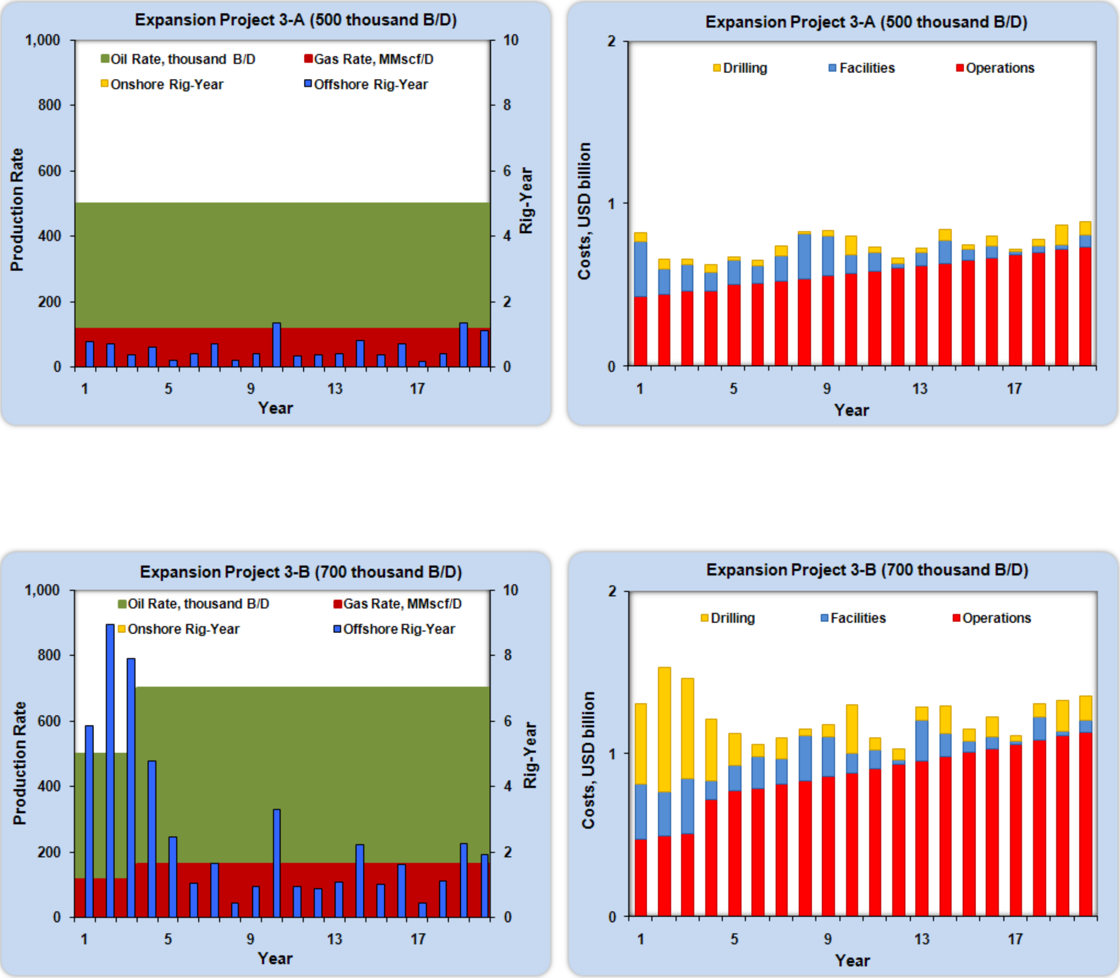


Fig. 4.6c—Expansion project E3.

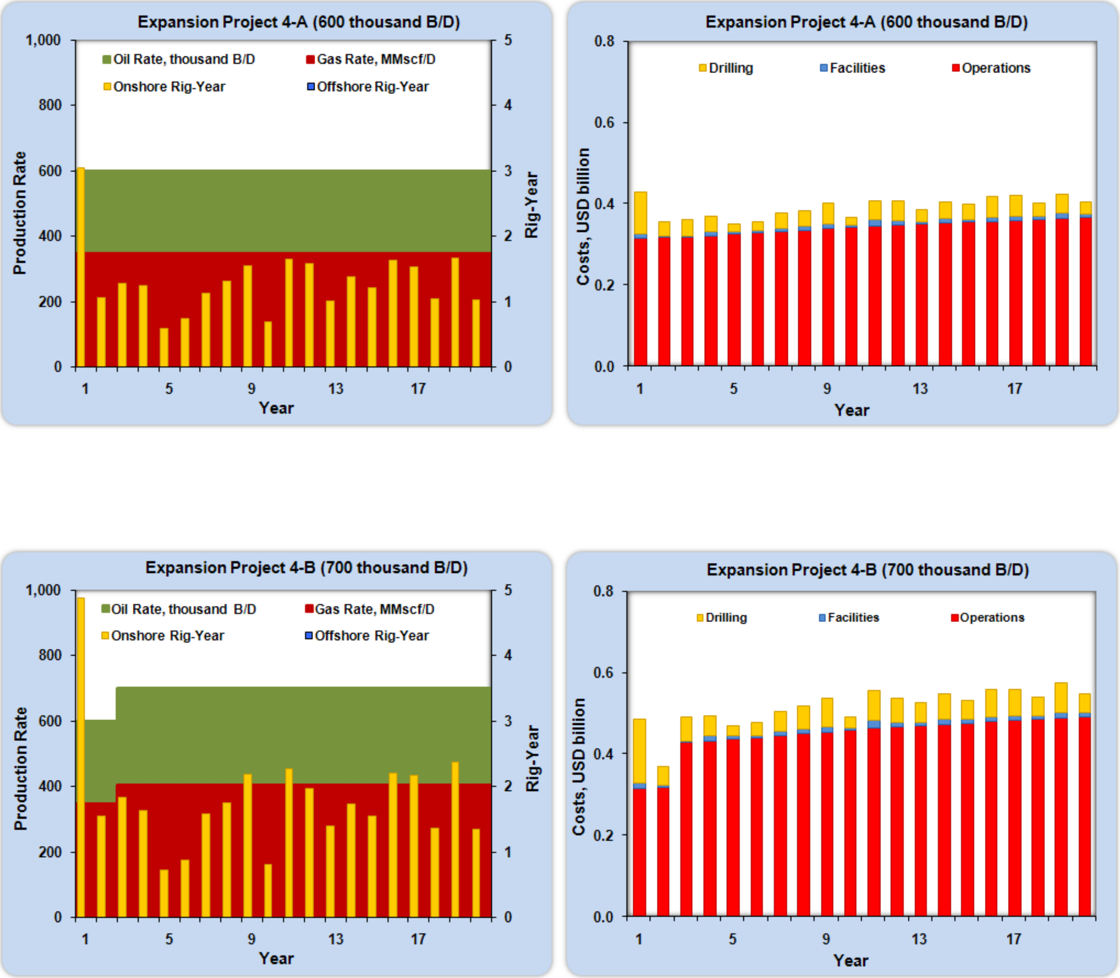


Fig. 4.6d—Expansion project E4.

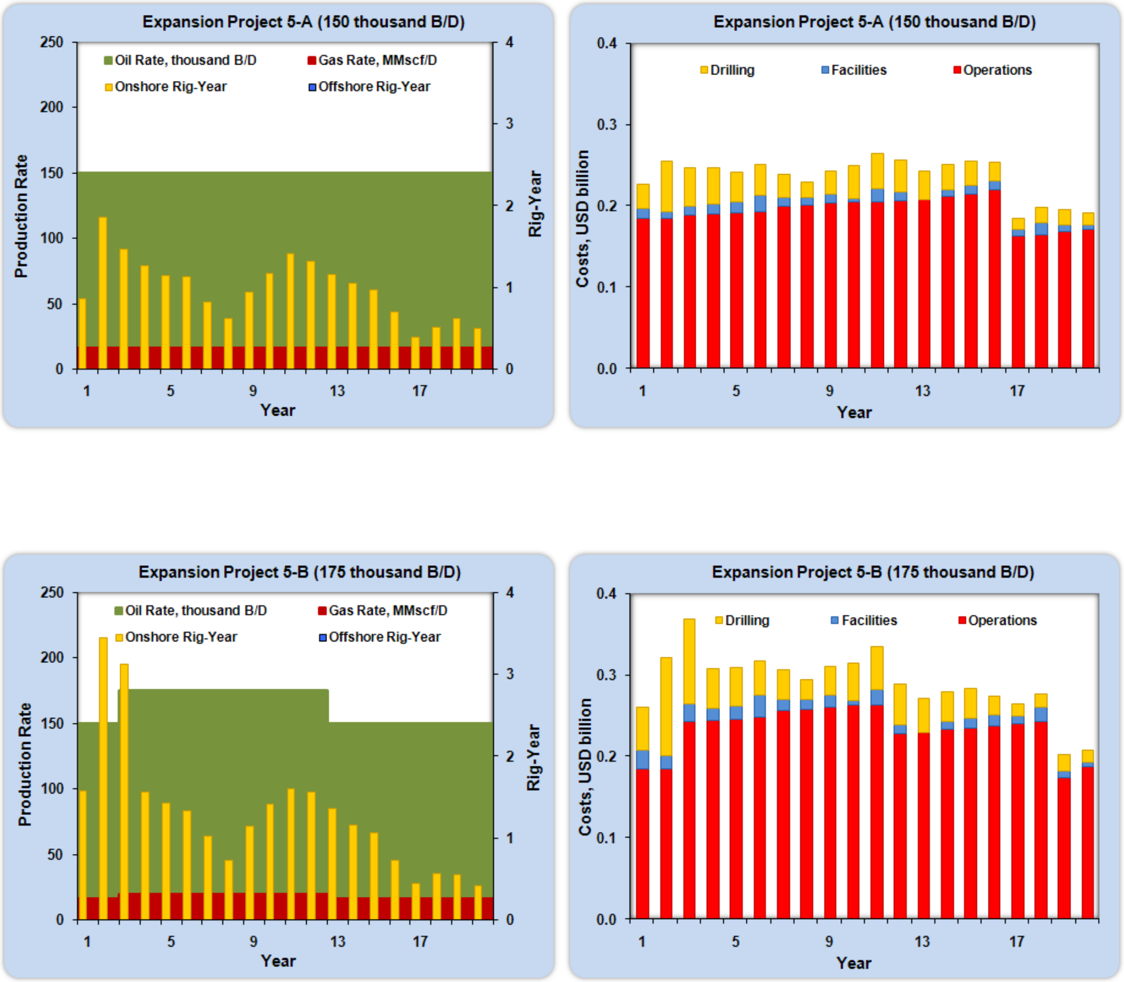


Fig. 4.6e—Expansion project E5.

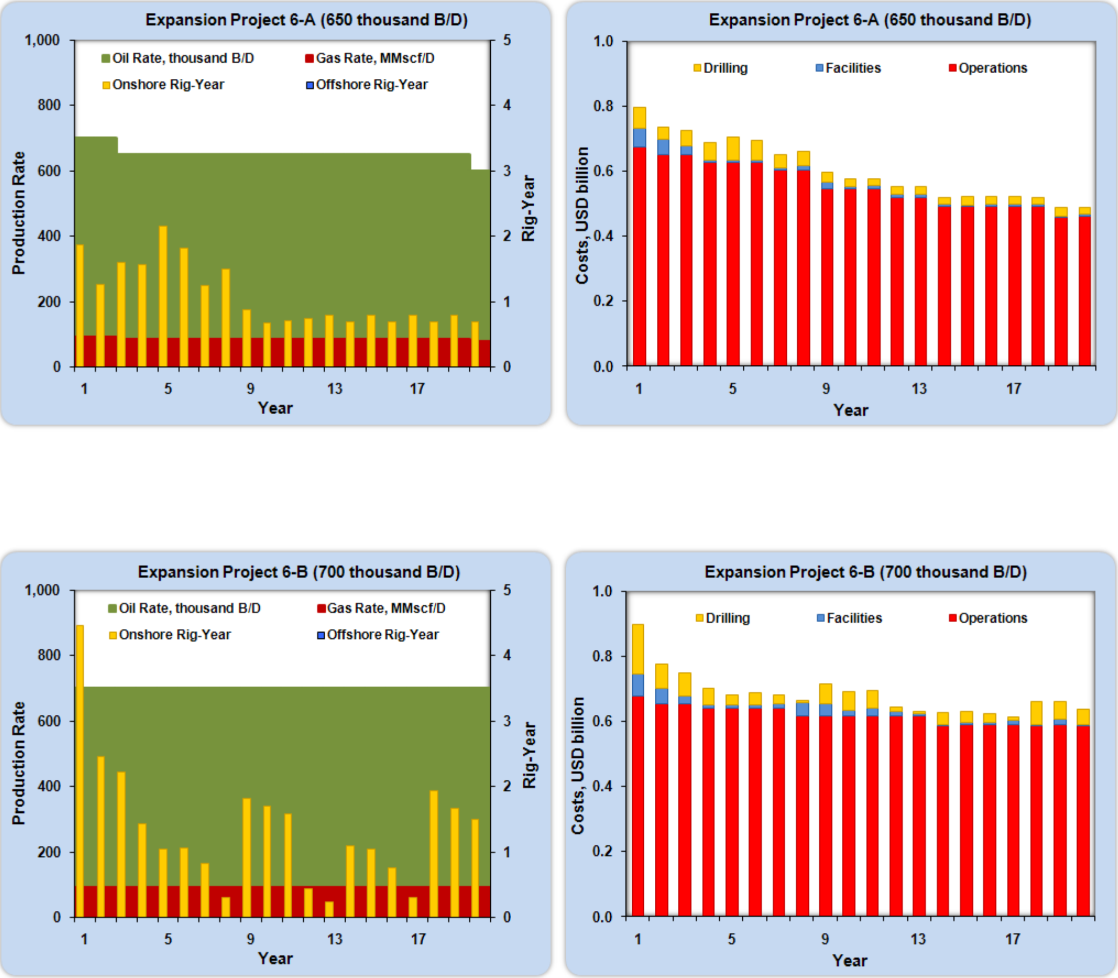


Fig. 4.6f—Expansion project E6.

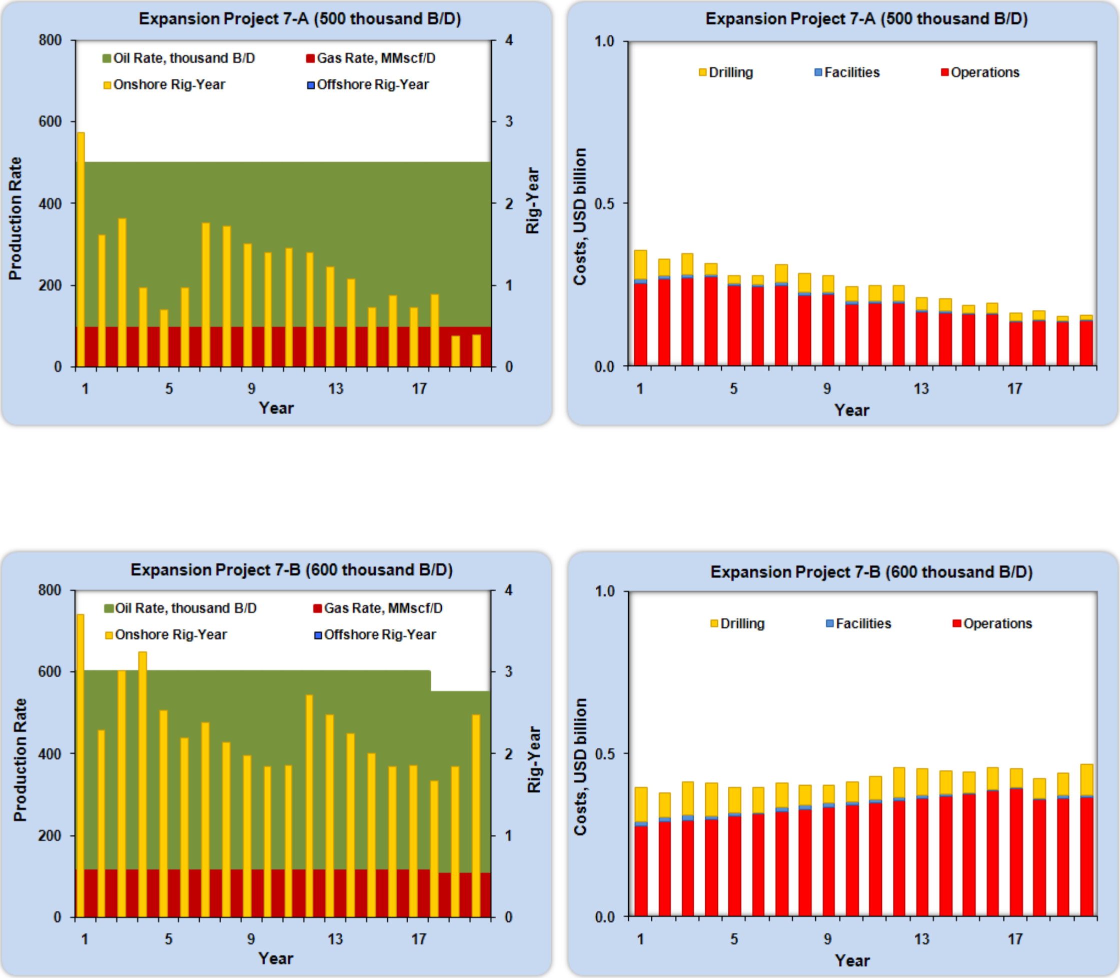


Fig. 4.6g—Expansion project E7.

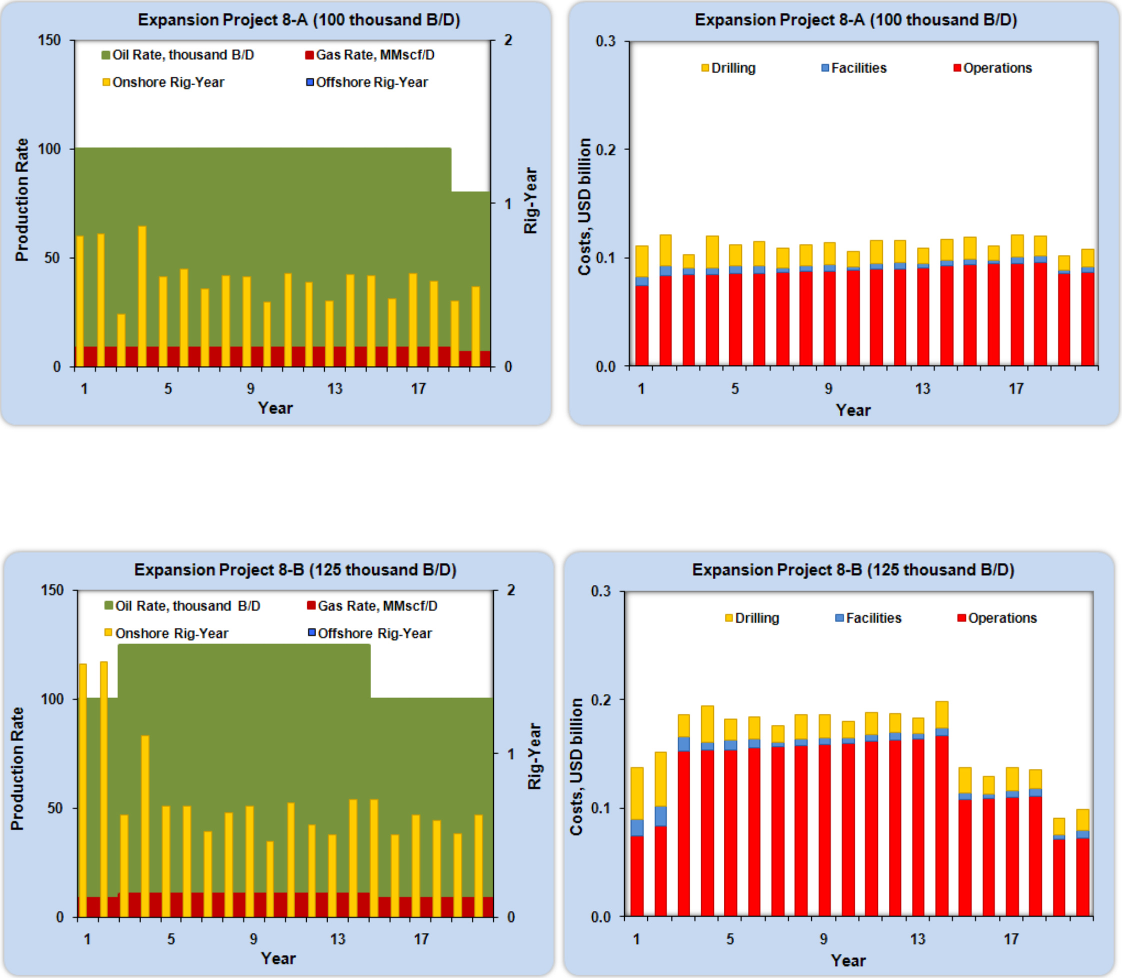


Fig. 4.6h—Expansion project E8.

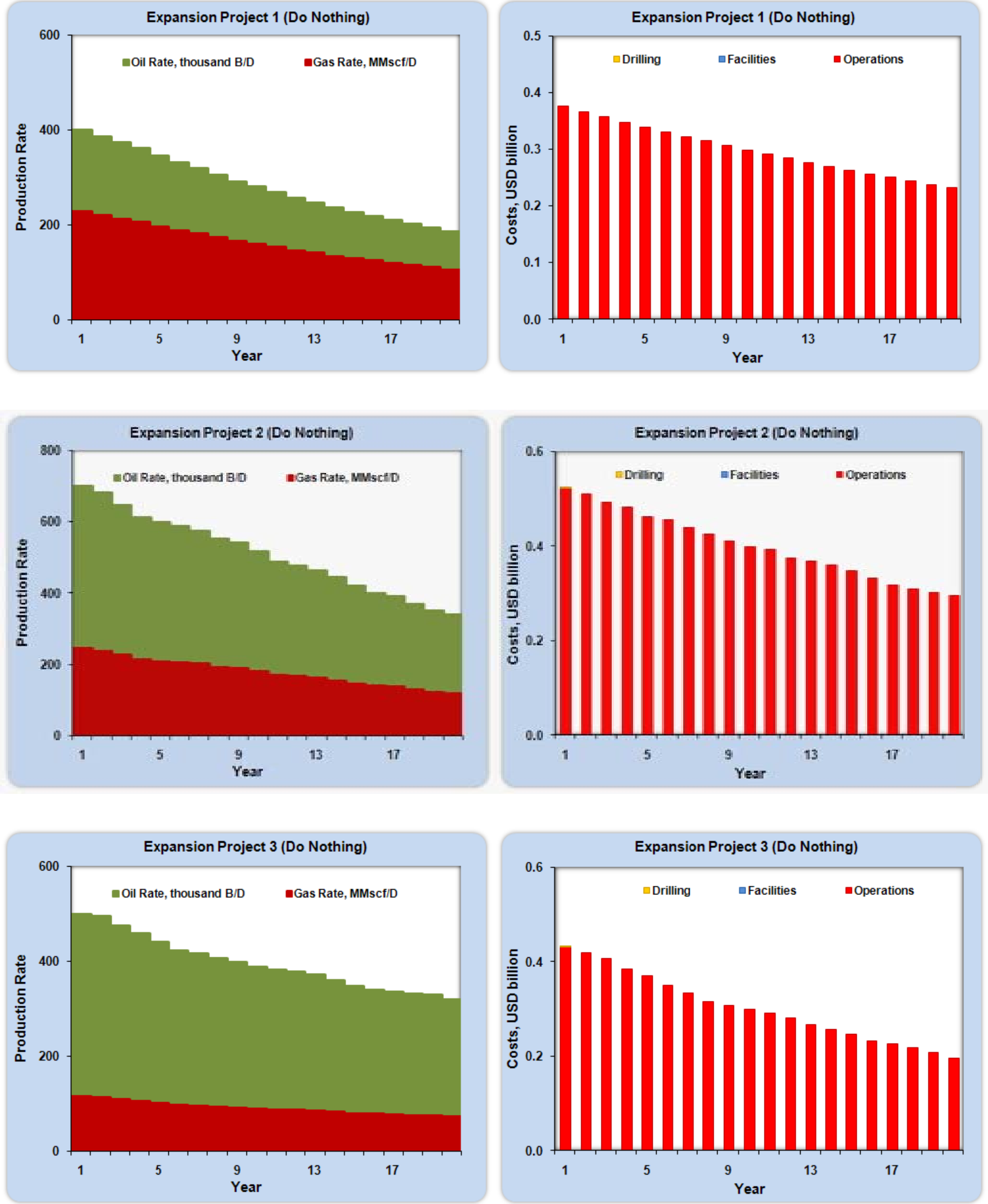


Fig. 4.7a—No-drilling cases for expansion projects E1 to E3.

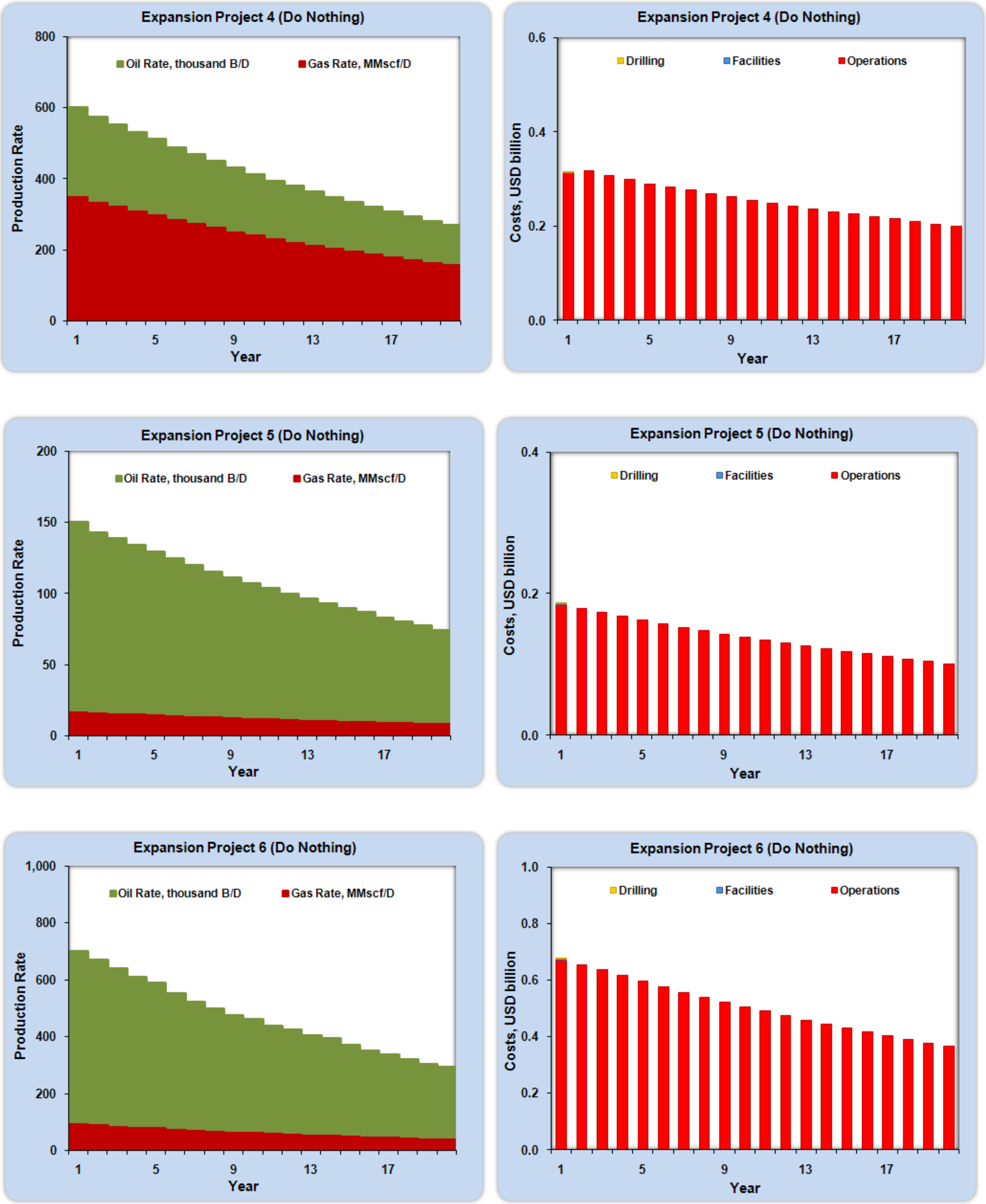


Fig. 4.7b—No-drilling cases for expansion projects E4 to E6.

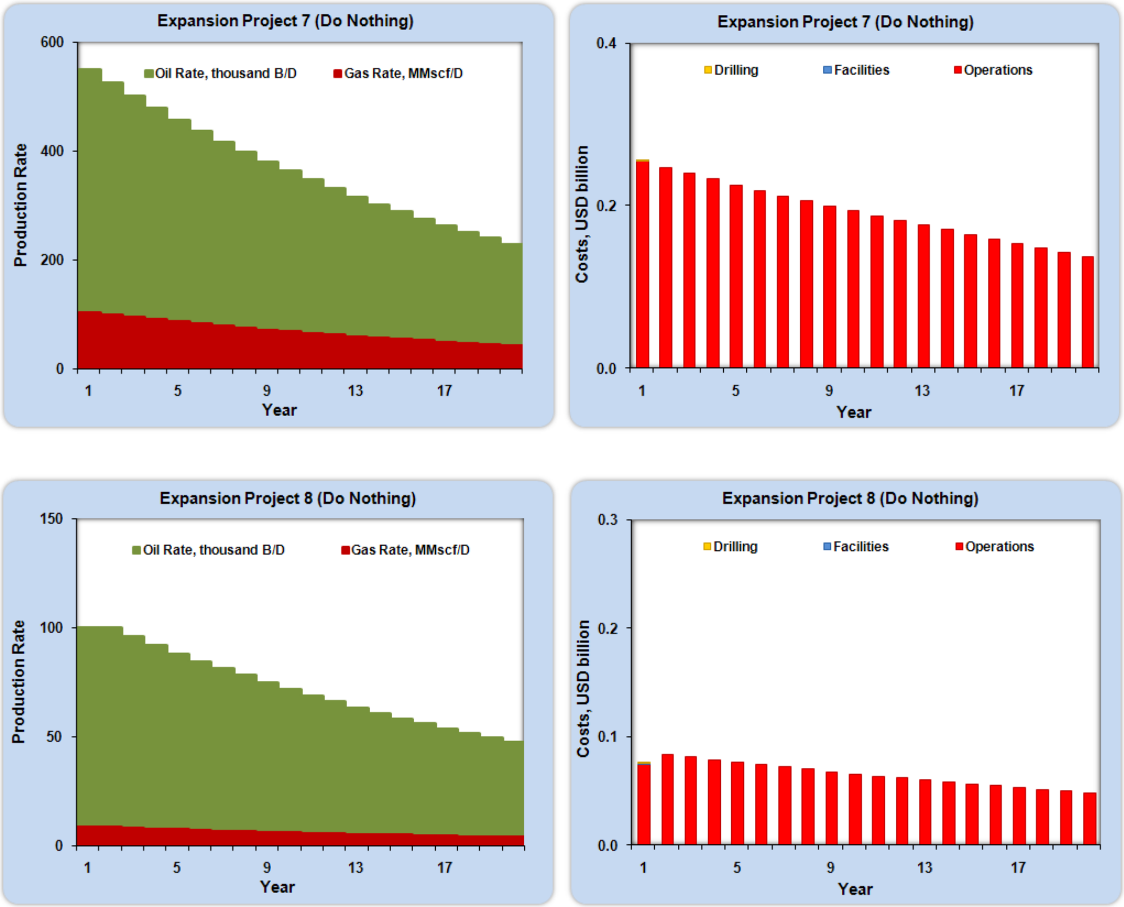


Fig. 4.7c—No-drilling cases for expansion projects E7 and E8.

The expansion projects involve eight existing fields producing a total of 3.65 million B/D. Expansion projects E1 to E8 consist of two options each. The data of the eight expansion projects are illustrated in **Figs. 4.6a through 4.6h**. Each expansion project has the option of increasing production or maintaining field existing levels. Expansion project E1 produces 400 thousand B/D of oil and 228 MMscf/D of associated gas. The field is located offshore. Fig. 4.6a shows the following two options.

- Option A: maintain current oil production level at 400 thousand B/D and associated gas level at 228 MMscf/D.
- Option B: expand oil production level to 450 thousand B/D and associated gas level to 257 MMscf/D.

The cases of no-drilling for expansion projects E1 to E8 are included in **Figs. 4.7a through 4.7c**. The no-drilling cases will be used to perform incremental analysis when evaluating the economic performance of expansion projects. The incremental analysis of expansion projects simplifies their comparisons to development projects.

CHAPTER V

APPLICATION OF GA IN PETROLEUM PROJECTS SCHEDULING

5.1 Petroleum Projects Selection Schedule

All investment projects presented in the previous chapter should be selected since they all have positive NPV discounted at 10% hurdle rate and the IRR of all projects exceeds the minimum required rate of return. However, limited resources will disapprove such decision. Mathematical formulation and GA developed in previous chapters will be applied to select the projects that maximize NPV and meet the number of limitations in several periods. The algorithm will be used to optimize scheduling of 22 development projects and eight expansion projects (two options for each of the eight expansion projects) presented in the previous chapter. The example problem will analyze four constraints: capital budget, operating budget, onshore rigs level, and offshore rigs level. The production level can be added as a constraint to meet a committed target production rate. However, this might exclude higher value solutions which do not meet the specified production target. The model evaluates production levels in the entire planning horizon of highly fit feasible solutions. The GA will be applied to an integrated framework comprising the economic models of the development and expansion projects and the associated constraints over the 10-year planning horizon. The example problem presented in this chapter is hypothetical but similar to the application that motivated this work.

5.2 Constraints and Assumptions

Increasing the number of constraints in several periods poses challenges in computing and analyzing optimal solution. The projects will be scheduled to maximize economic performance subject to four constraints over 10-year planning horizon. Each constraint consists of multidimensional attribute of 10 periods. This imposes a total of 40 different constraints on the problem. **Fig. 5.1** depicts the base case constraints for the levels of capital budget, operating budget, onshore rigs, and offshore rigs in each period of the 10-year planning horizon.

A fixed limit on investment capital, known in literature under capital rationing, complicates investment appraisals and obstruct the company to undertake all attractive opportunities. In the proposed base case, the capital budget is increased gradually from USD 5 billion in the first year to reach USD 8 billion in years nine and 10. This funding includes drilling wells, production facilities, wells equipment, and upstream infrastructure. Another complication may arise from the amount of budget available for both fixed and variable operating costs. The availability of talented manpower and its cost is a significant part of the operating budget forecast. The operating budget is more than doubled from USD 3.3 billion in year one to USD 7 billion in year 10.

Drilling wells are considered as a critical activity in any development or expansion project. Shortage of onshore and offshore drilling rigs can influence the project. The activity levels in the oil and gas industry have increased due to high oil prices which imposed limits on the availability of rigs. The limitations of onshore and offshore rigs create two sets of constraints. The onshore rigs level is increased from 22 rig-year in year one to reach 38 rig-year in year 10. The offshore rigs level is also increased from 16 rig-year in year one to reach 24 rig-year in years nine and 10. The production level is not incorporated in the model directly as a constraint to allow evaluating solutions of higher NPV which may not meet the required production rate.

The proposed model considers the following assumptions and business rules. Some of the assumptions and rules are region-specific and defined for the application that motivated this work.

- Investment projects are irreversible. The projects can be selected once and remain active throughout the project life.
- The model does not allow partial development of the projects. The model is formulated based on 0-1 binary decision variable.
- No capital deferral is allowed. The amount of capital not used in certain period will not be used in subsequent periods.
- Returns will not be reinvested, capital will be defined and projected without direct link to revenues.
- Projects 21 and 22 must remain under development. They are included to account for their required resources.
- All cost estimates are in 2008 base year dollars. The model will apply the proper escalations for capital and operating costs according to the year of selection.

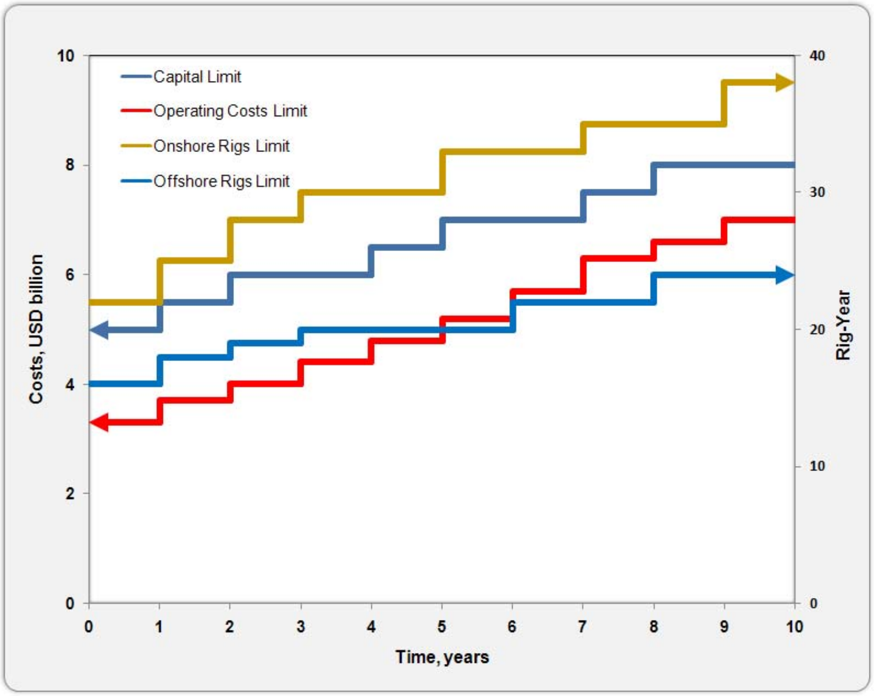


Fig. 5.1—Base case constraints in each period of the 10-year planning horizon.

- The rig levels involve reserves development drilling and does not account for exploration activities.
- Capital costs include drilling, wells equipment, upstream infrastructure and production facilities such as pipelines, platforms, processing equipment, vessels and facilities expansions.
- New onshore facilities are generally assumed to be constructed over a period of two years. On the other hand, new offshore facilities are assumed to be constructed over a period of three to four years.

- One of the two options of the 8 expansion projects must be selected in year one. The proposed expansion projects are for producing fields where production should not be discontinued.
- The cash flow is computed over the entire life of a project and not just for the number of periods in the planning horizon.

5.3 Optimizing Projects Selection Schedule

5.3.1 Base Case

This section illustrates the performance of the proposed GA which is coded as macros written in Microsoft Visual Basic for Applications (VBA) with Excel spreadsheets. The solution involves projects selection from the presented development and expansion projects to maximize NPV and satisfy the constraints identified in the previous section in each of the 10 periods of the planning horizon.

Construction greedy algorithm was first implemented to obtain an initial estimate of the 30-project problem. The greedy algorithm initially determines a feasible selection schedule with a NPV of USD 484 billion for the reference oil and gas prices. **Figs. 5.2a through 5.2c** illustrates the oil and associated gas production schedule, the required capital and operating costs, and the required onshore and offshore rigs for the outcome of the construction algorithm. The GA was successfully implemented to generate numerous feasible selection schedules with higher NPV as illustrated in **Fig. 5.3**. The figure shows results of 500 generations with generation zero representing initial population. The sequence and timing of projects has significant effect on the economic performance of the assets. The GA generates a maximum NPV of USD 539 billion versus USD 484 billion from the greedy algorithm which improves the assets NPV by USD 55 billion over the 10-year planning horizon.

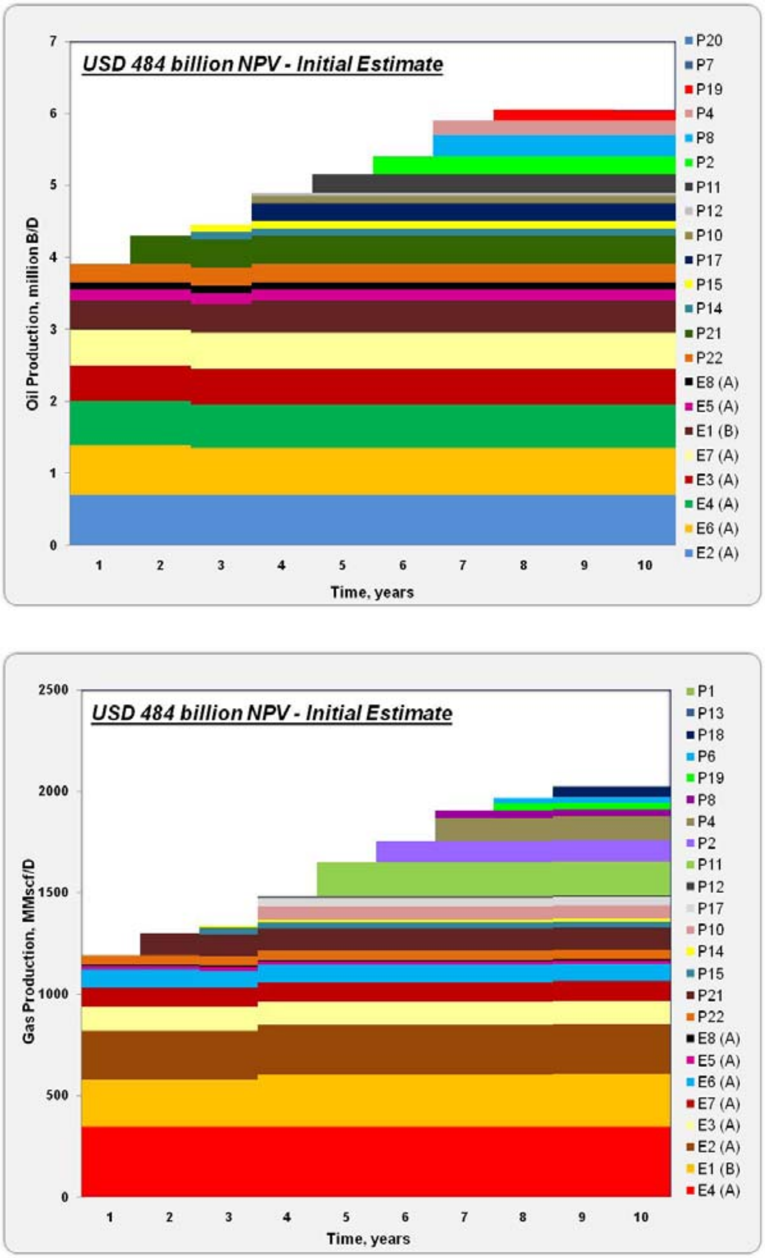


Fig. 5.2a Oil and gas production schedules of construction algorithm base case.

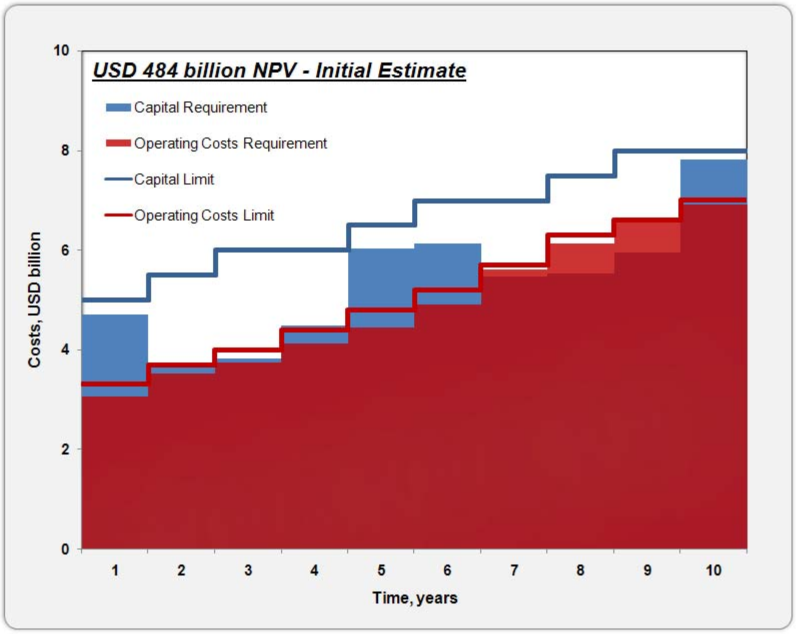


Fig. 5.2b Costs requirements of construction algorithm base case.

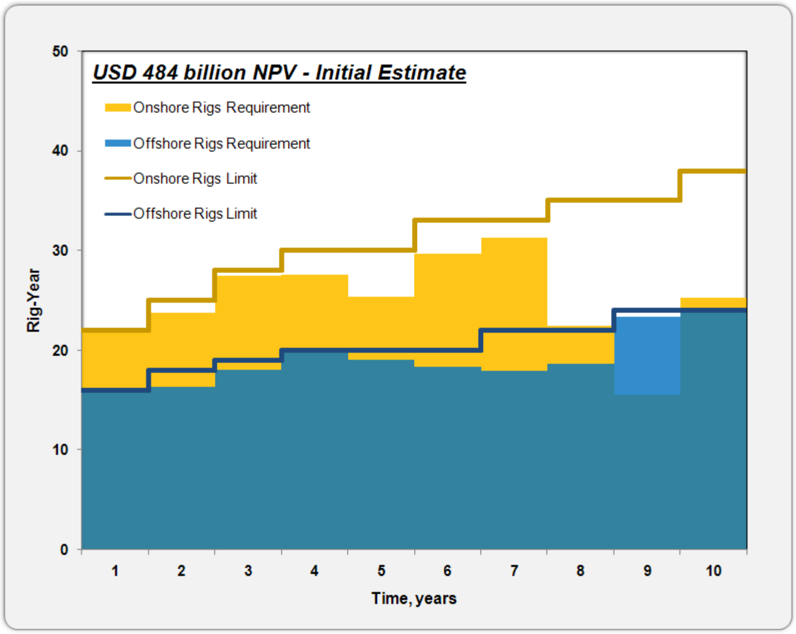


Fig. 5.2c Rigs requirements of construction algorithm base case.

The outcomes of the proposed GA model are shown in **Figs. 5.4a through 5.4d**. The figures compare oil and associated gas production schedules, the budget requirements for capital and operating costs, and the rig requirements for onshore and offshore drilling. Three different selection schedules of the highest NPV are presented. The oil production rate of the highest NPV outcome expands from 4.0 million B/D in year one through 5.35 million B/D in year five to reach maximum production rate of 6.45 million B/D in year 10. The associated gas also expands from 1,211 MMscf/D in year one to 1,678 MMscf/D in year five and 2,133 MMscf/D in year 10. **Fig. 5.5** shows 25 schedules of the highest NPV of the GA base case run.

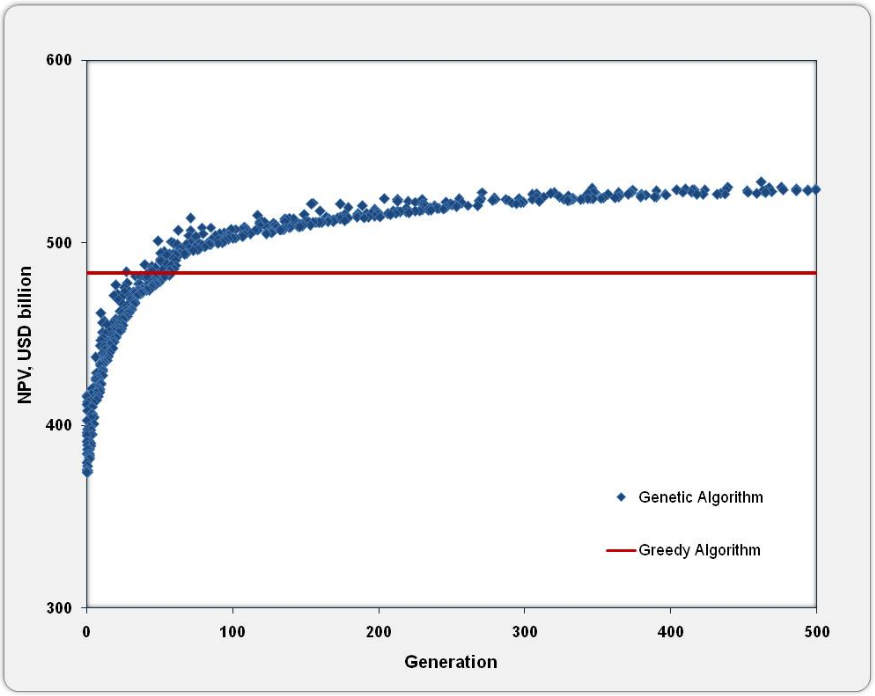


Fig. 5.3—Model performance of the base case.

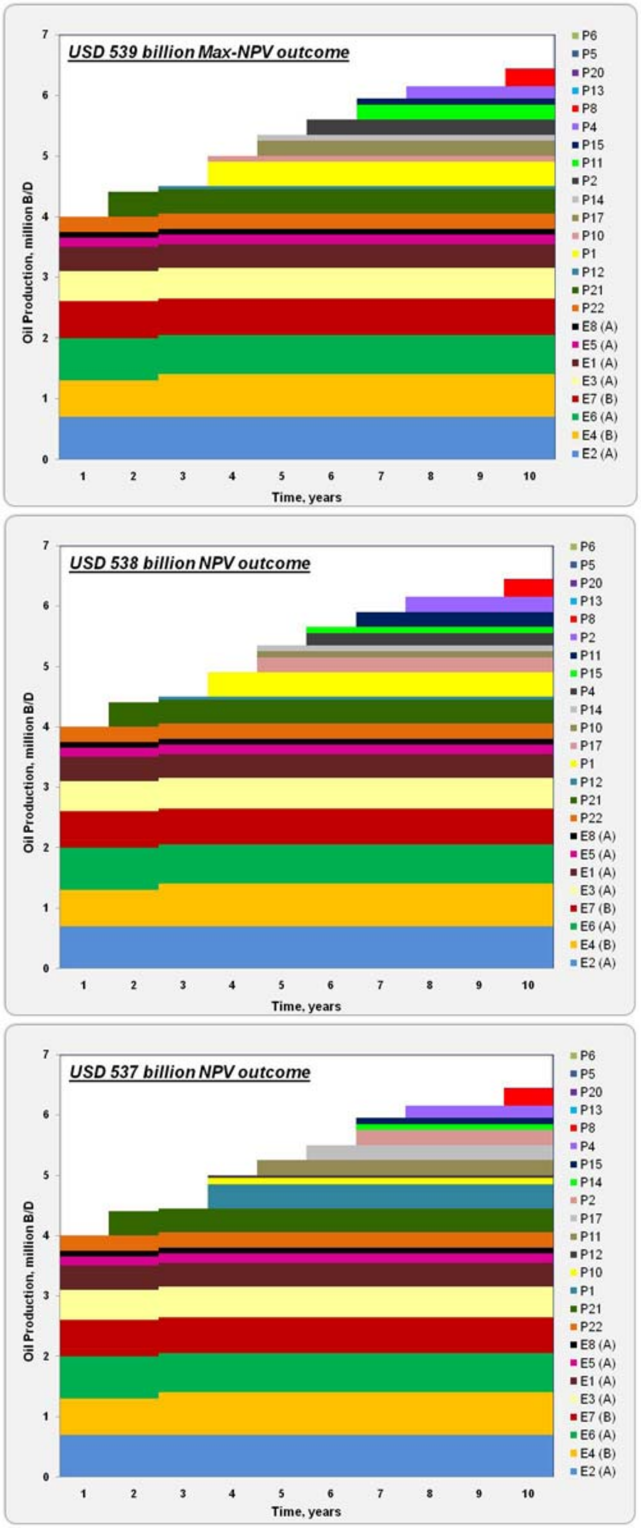


Fig. 5.4a—Oil production schedules of GA base case.

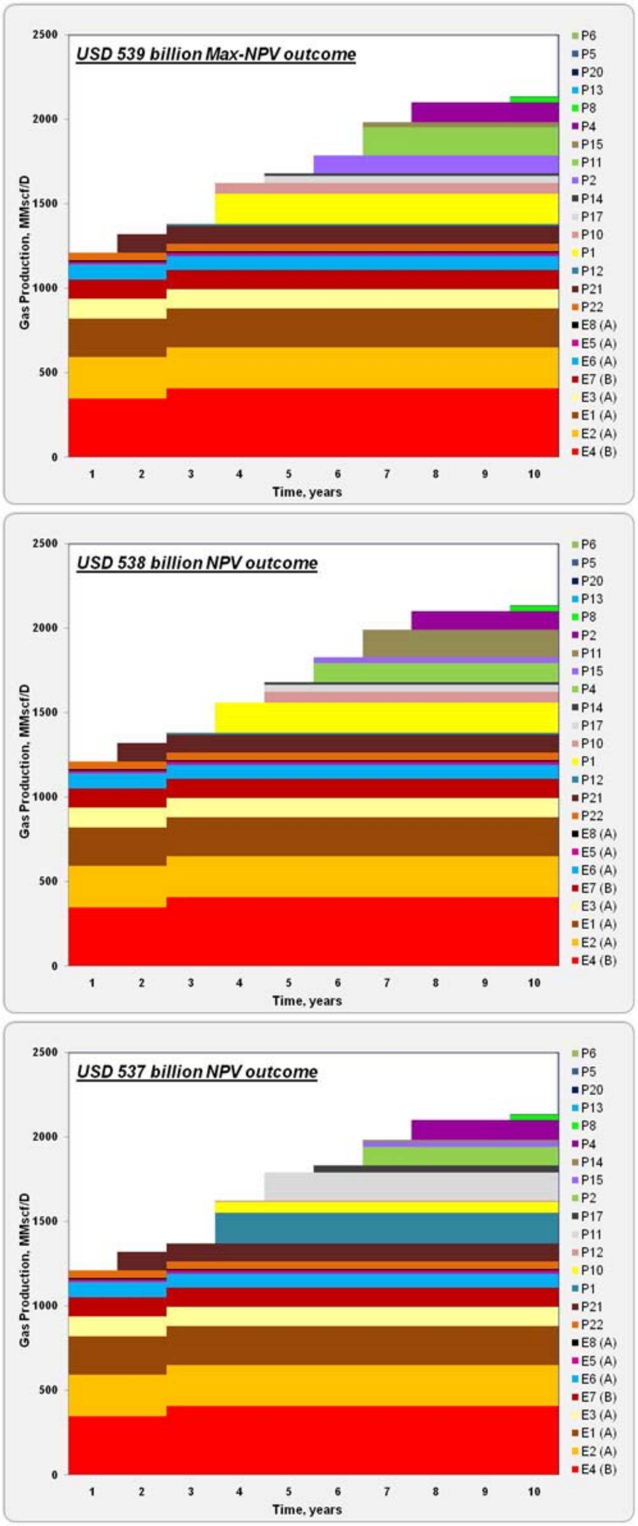


Fig. 5.4b—Gas production schedules of GA base case.

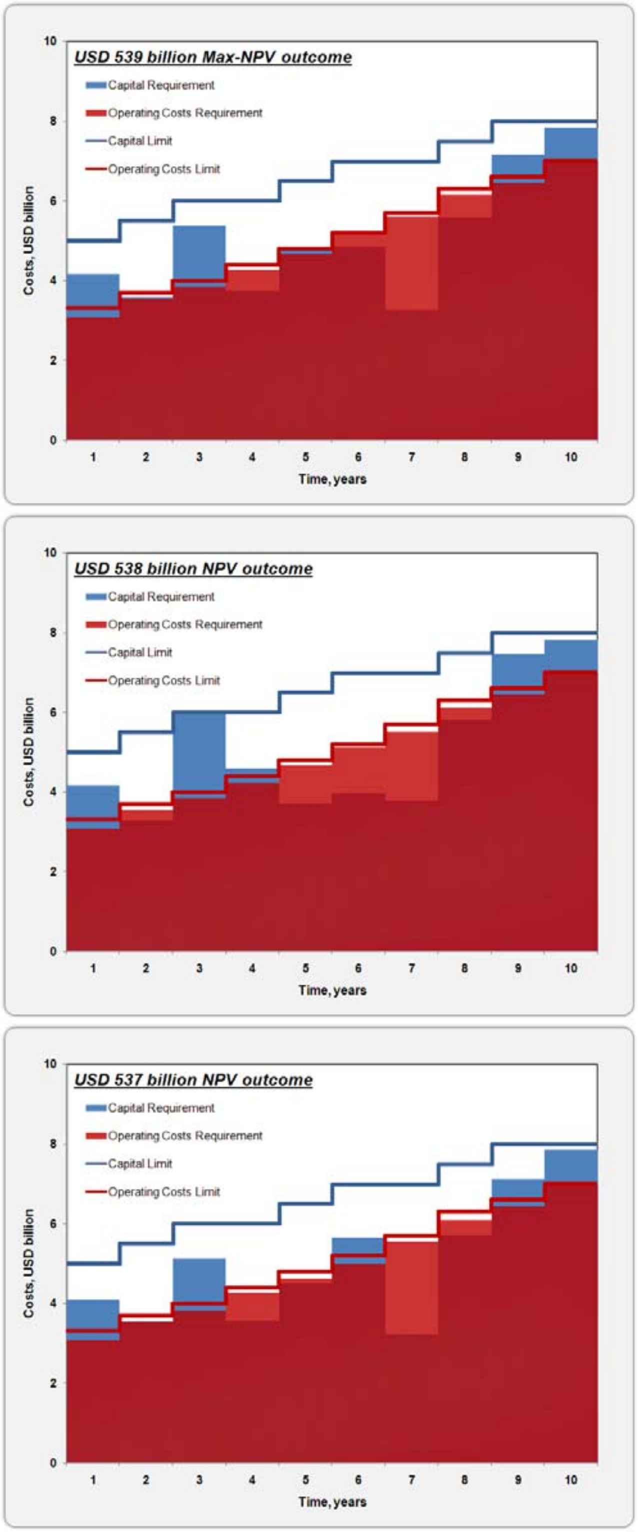


Fig. 5.4c—Costs requirements of GA base case.

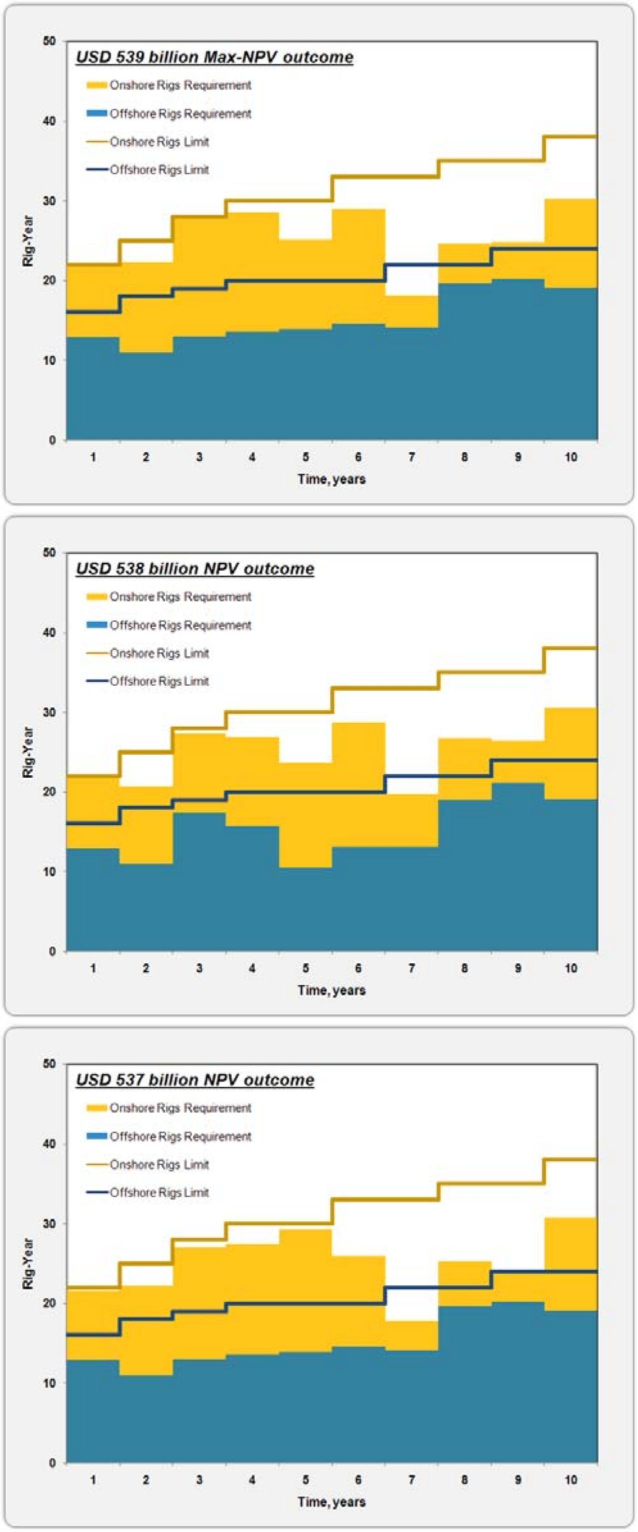


Fig. 5.4d—Rigs requirements of GA base case.

	Year										
No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**NPV**
1	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11	17 4	2 15		8 14	9 7		20 13	538.595
2	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11 4	17 15		2 14		9 7 8		20 13	538.292
3	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11	17 14 4		2 15	8	9 7		20 13	538.081
4	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11	15 14 4	2	8	17	9 7		20 13	537.883
5	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11	6 15	2 14		17 4	9 7 8		20 13	537.729
6	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11	17 4	15 2	14		9 7 8		20 13	537.447
7	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11	2 14 4	15	17		9 7 8		20 13	537.273
8	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	17 4	14 15	2	11		9 7 8		20 13	537.205
9	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	17 4	11	15	14 2		9 7 8		20 13	537.092
10	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	17	11 4	15	14 2	8	9 7		20 13	536.917
11	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11	17 4	15 2		14	9 7 8		20 13	536.749
12	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11	17 4	2 14		15	9 7 8		20 13	536.714
13	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11 4	15	2 14	17		9 7 8		20 13	536.708
14	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11	17 4	2	14 15		9 7 8		20 13	536.602
15	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11	17	14 15 4 2			9 7 8		20 13	536.591
16	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11	17 15	4	2 14	8	9 7		20 13	536.435
17	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	17 4	11		14 2 15		9 7 8		20 13	536.247
18	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	2	11 4	14 15	17		9 7 8		20 13	536.232
19	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11	15 14	4 2	8	17	9 7		20 13	536.200
20	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11	8	14 15	2 4	17	9 7		20 13	536.157
21	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11	17 4	15 2			9 7 8 14		20 13	536.149
22	21 22 E1A E2A E3A E4B E5A E6A E7B E8A 16	1	11 4	10	2	17 14 15		8 9 7		20 13	536.057
23	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11		17 2 14 4 15		8	9 7		20 13	535.942
24	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	2	17 4	15 14	11		9 7 8		20 13	535.937
25	21 22 E1A E2A E3A E4B E5A E6A E7B E8A	1 12 10	11	17 4	2	15	14	9 7 8		20 13	535.905

Fig. 5.5—Model outcome for highest 25 schedules of GA base case.

5.3.2 Uncertainties of Oil Prices

Future oil prices are highly uncertain and extremely difficult to project. This uncertainty in oil prices presents substantial risk on petroleum project investments of large scale. The proposed GA model evaluates schedules at reference, high and low price cases from AEO2007 by EIA. **Fig. 5.6** depicts model performance for the three price cases.

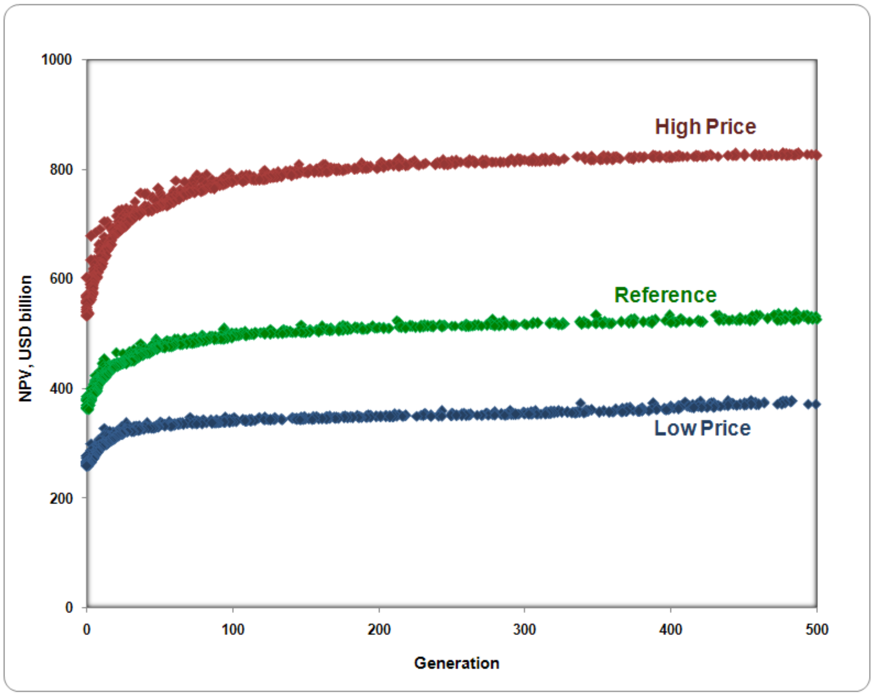


Fig. 5.6—Model performance of different oil prices.

The high oil price case was applied in the greedy algorithm to construct an initial NPV estimate of USD 745 billion. The proposed model generates a selection schedule of maximum NPV of USD 829 billion. This improves the aggregated NPV of the high oil price case by USD 70 billion over the 10-year planning horizon. The low price case economically support all presented development and expansion projects. The greedy algorithm constructs an initial NPV estimate of USD 341 billion for the low oil price case. The proposed GA model improves the selection schedule and generates a maximum NPV of USD 378 billion.

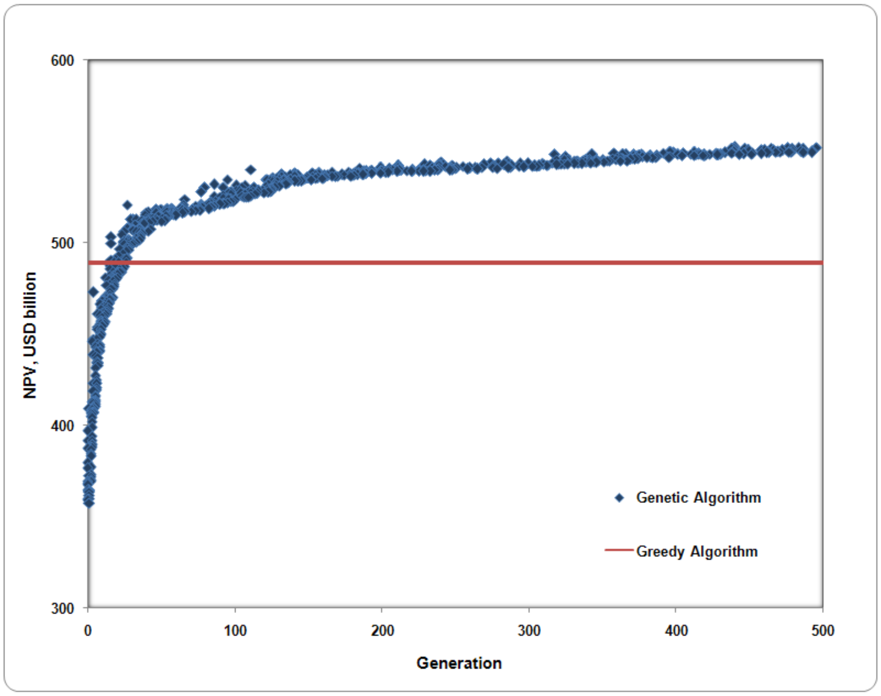


Fig. 5.7—Model performance of the 10% operating budget increase case.

5.3.3 Flexibility of Constraints

The outcome of the base case run shows that the required budget for the operating costs is close-fitting to the available operating budget throughout the planning horizon (Figs. 5.2b and 5.4c). The proposed method seeks to attain the optimal selection schedule of petroleum investment projects with rigid constraints over the planning horizon. However, constraints are not completely rigid in practice. The assumption of rigid constraints moderates the complexity of the problem which involves several constraints in multiperiod horizon. A case of 10% increase in operating budgets throughout the planning horizon will be investigated.

A construction solution was first obtained from the greedy algorithm with a NPV of USD 489 billion for the reference oil and gas prices. The proposed GA model improves the NPV by USD 62 billion to reach a maximum NPV of USD 554 billion. **Fig. 5.7** illustrates the performance of the model for this case. **Figs. 5.8a through 5.8d** illustrates the oil and gas production schedule, the required capital and operating costs, and the required onshore and offshore rigs for the outcome of this case where operating budget was increased by 10% over the entire planning horizon.

5.3.4 Projects Staging

The presented model does not allow partial development of the proposed projects. The projects are selected based on 0-1 binary discrete decision variables. The development of the projects in stages may improve the assets value due to scarcity of resources. For instance, development projects P3 and P5 generate high NPV but require intensive resources because of the projects sizes. The base case constraints and the 10% increases in operating budget would not allow such investments to be selected to improve the assets value.

This section investigates the benefits of staging some of the sizable projects. The case will assess staging four development projects which are P3, P5, P9 and P13 as shown in **Fig. 5.9**. Three development stages will be considered for projects P3 and P5. The other two projects P9 and P13 will be developed in two stages.

The staging of the four projects produces some improvements in the value of the assets. The staging case generates a maximum NPV of USD 580 billion versus USD 554 billion from the 10% operating budget increase case which improves the assets NPV by USD 26 billion over the 10-year planning horizon. **Figs. 5.10a through 5.10c** illustrate the outcome of the model for the staging case. The oil production rate expands from 4.0 million B/D in year one through 5.2 million B/D in year five to reach maximum production rate of 7.0 million B/D in year 10. This case offers additional oil production capacity of 550 thousand B/D in year 10 over the base case (7.0 versus 6.45 million B/D). The gas production rate also expands from 1,211 MMscf/D in year one to 1,614 MMscf/D in year five and 2,280 MMscf/D in year 10. This generates additional gas production capacity of 147 MMscf/D in year 10 over the base case (2,280 versus 2,133 MMscf/D). Furthermore, the staging case produces better distribution of various resources requirements over the planning horizon.

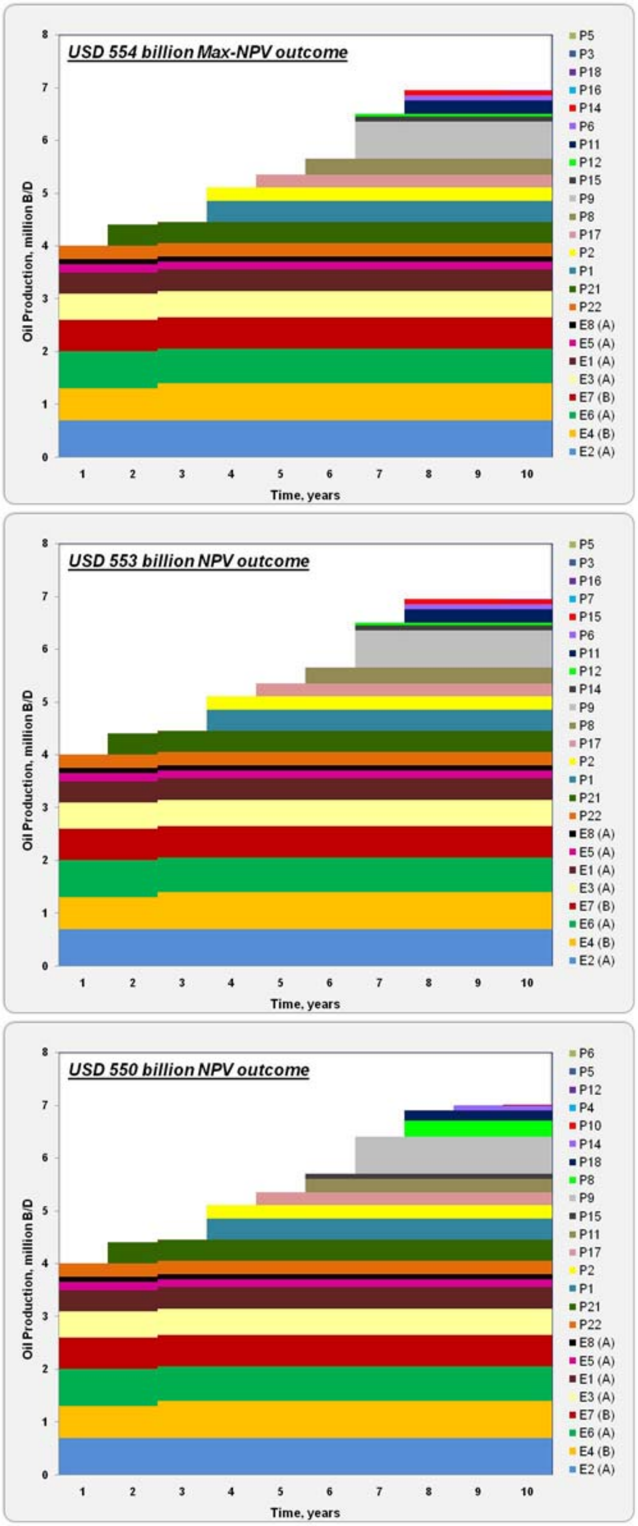


Fig. 5.8a—Oil production schedules of the 10% operating budget increase case.

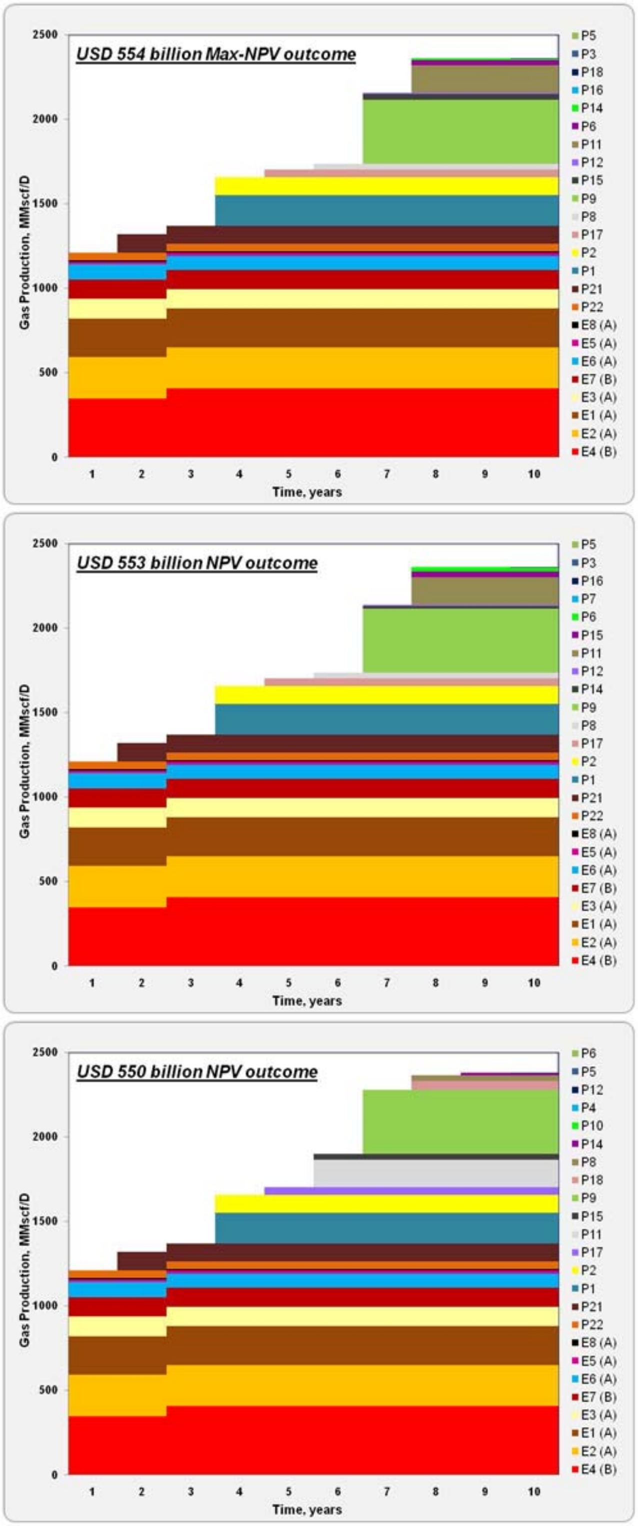


Fig. 5.8b—Gas production schedules of the 10% operating budget increase case.

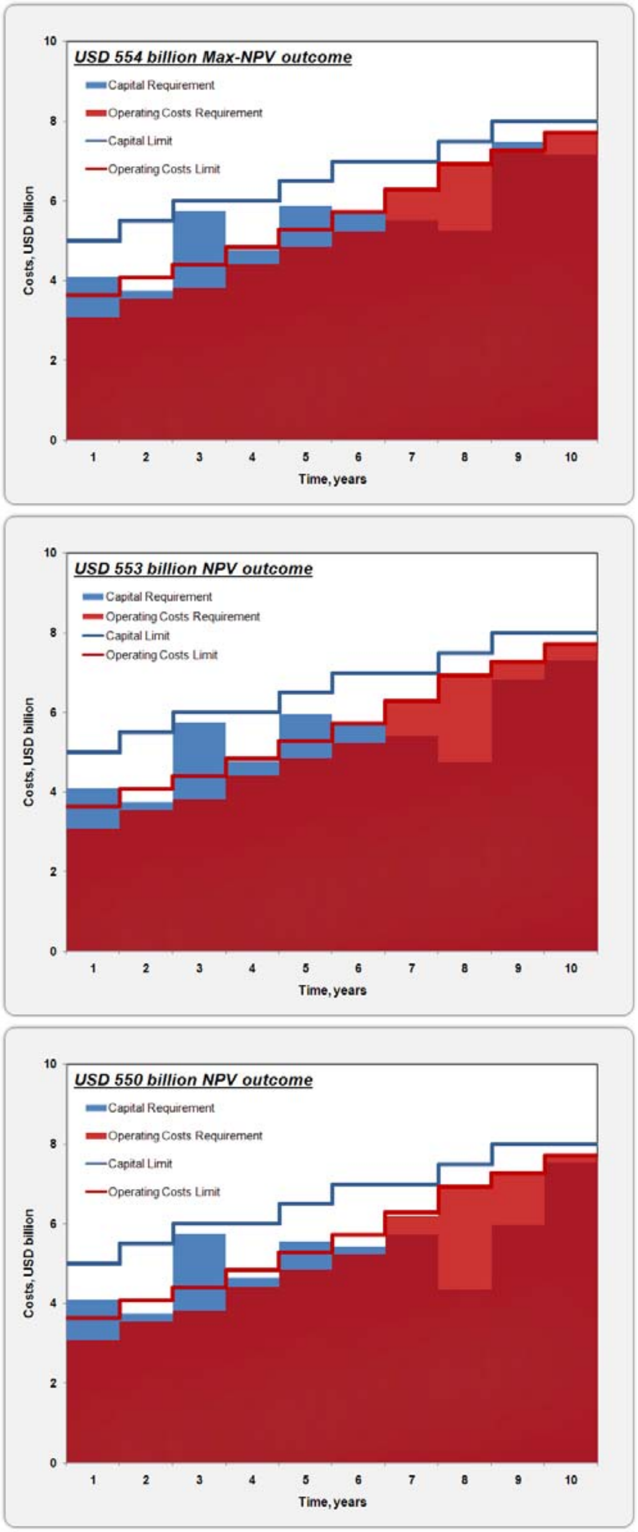


Fig. 5.8c—Costs requirements of the 10% operating budget increase case.

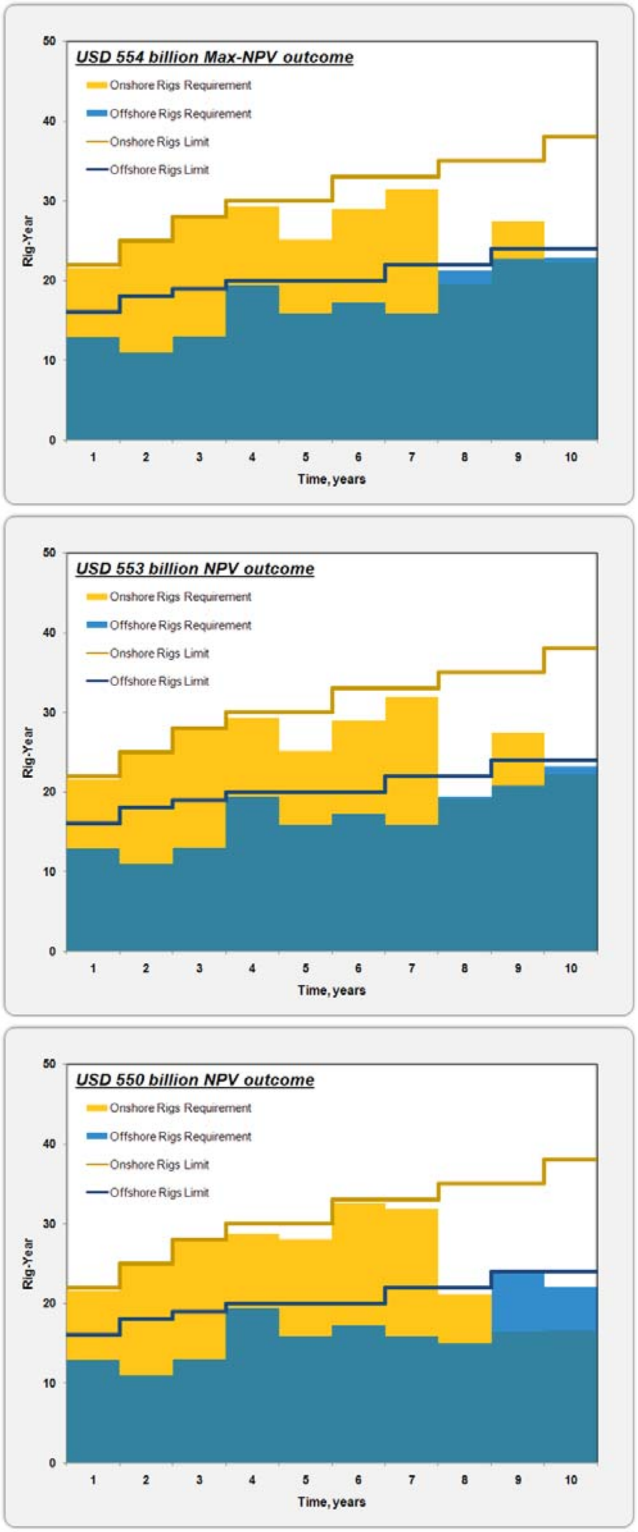


Fig. 5.8d—Rigs requirements of the 10% operating budget increase case.

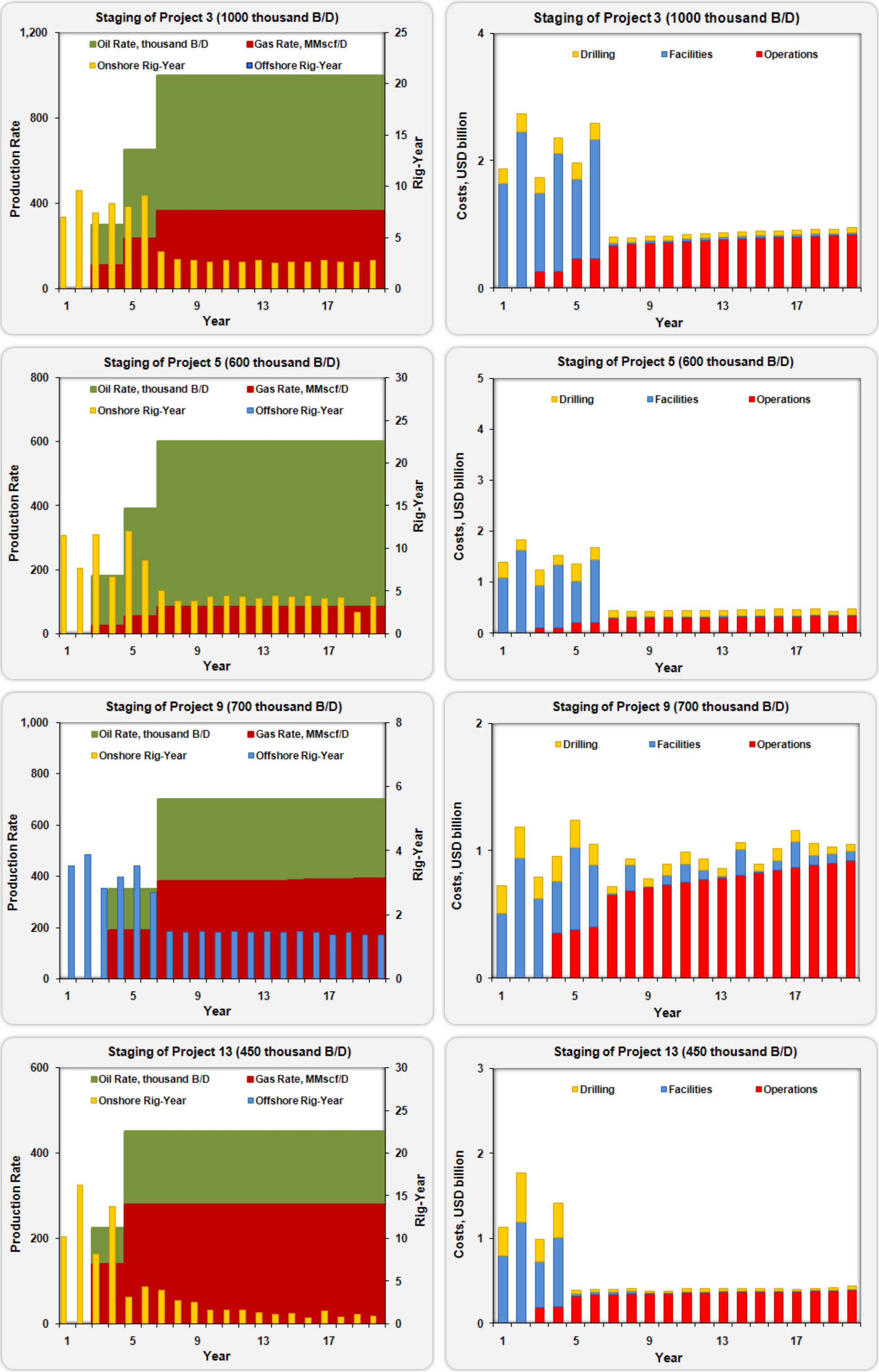


Fig. 5.9—Staging of four development projects: P3, P5, P9, and P13.

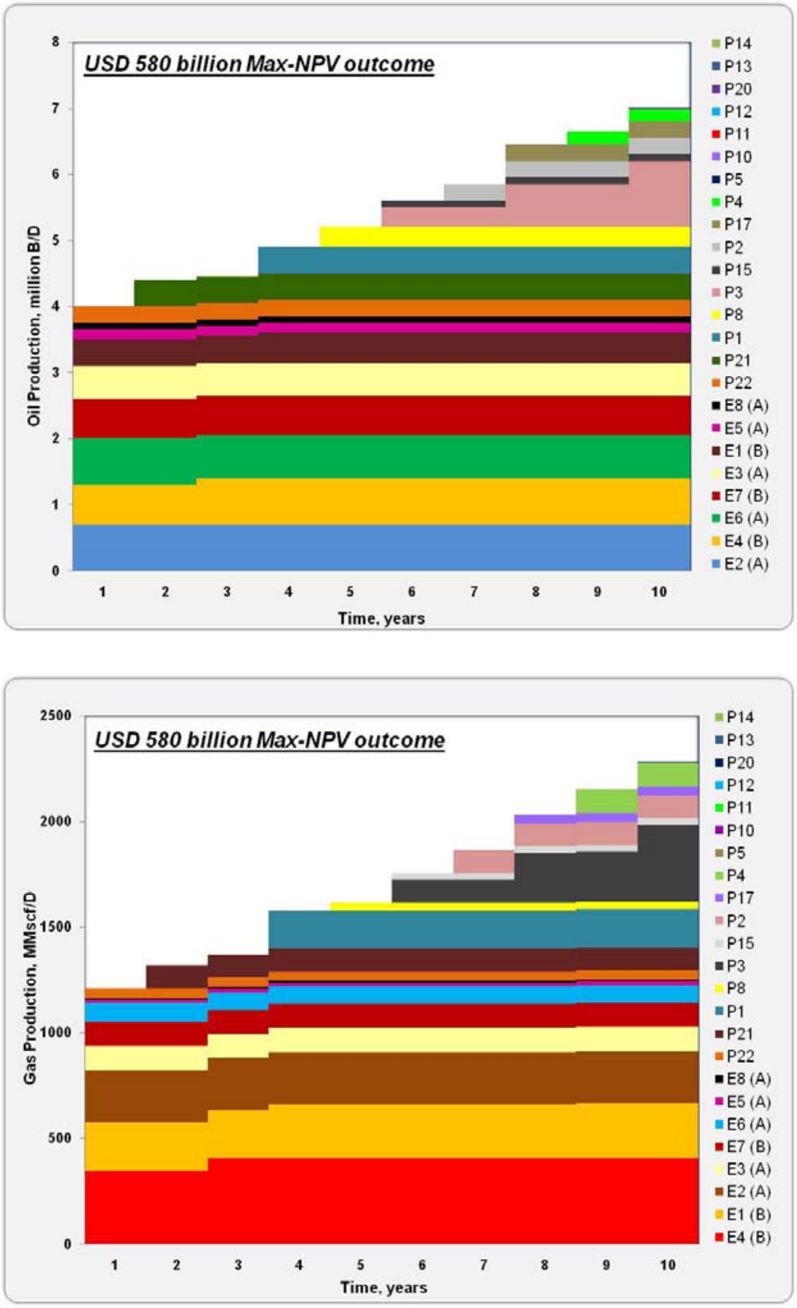


Fig. 5.10a—Oil and gas production schedules of the staging case.

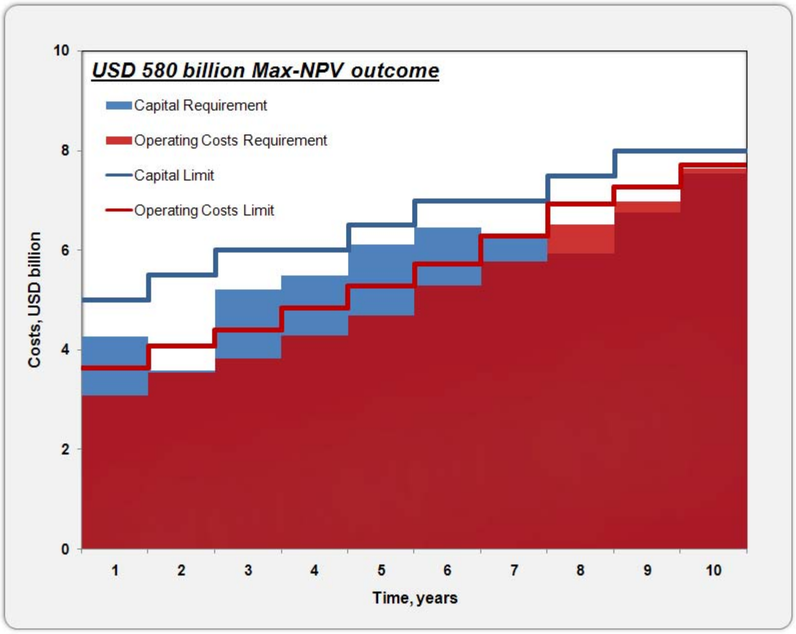


Fig. 5.10b—Costs requirements of the staging case.

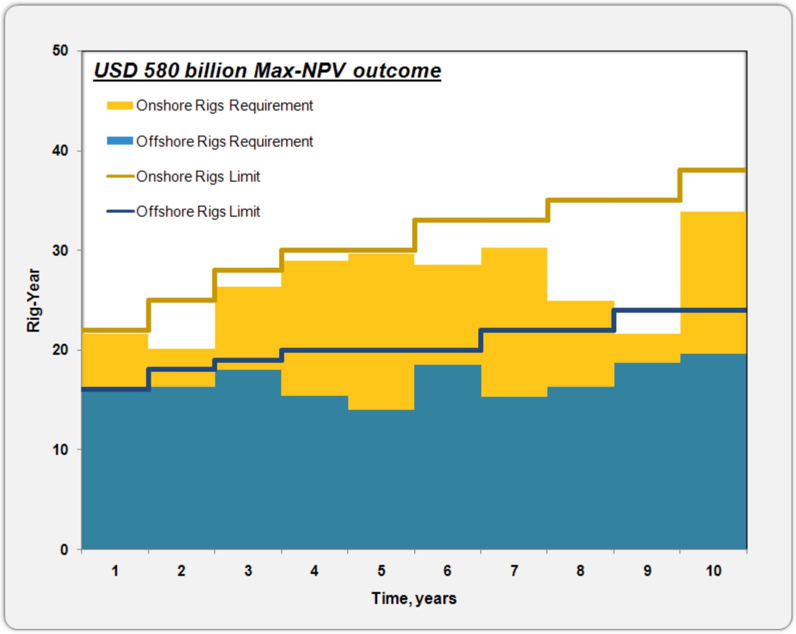


Fig. 5.10c—Rigs requirements of the staging case.

CHAPTER VI

CONCLUSIONS AND FUTURE RESEARCH

6.1 Conclusions

An integrated investment model permits the whole set of investment opportunities to be evaluated as a program to determine the best investment decision. This requires a mathematical formulation of the problem and application of proper optimization methods to solve it. Early applications of optimization methods and practices in the E&P generally involved investments associated with activities of individual or few neighboring projects. This work presents a new integrated model to optimize large number of petroleum development and expansion projects of large-scale under several resources constraints in multiple periods. A natural formulation of the problem involves binary decision variables to model the selection schedule of investment projects. The model also involves various levels of a number of required resources for the selected projects in each period of the planning horizon. The problem is very similar to a variant of the famous resource allocation Knapsack Problems with multi-constraints in multiple periods. The emphasis of the model is on metaheuristic GA to solve the computational complexity of the problem.

The proposed model was illustrated through a problem of 30 development and expansion projects in the upstream oil and gas industry. The problem maximizes NPV and involves resources constraints of capital budget, operating budget, onshore rigs level and offshore rigs level. The model also assesses target production levels in the various periods of the planning horizon. The example problem is only illustrative of the model and does not reveal real data.

A greedy algorithm was first utilized to construct an initial estimate of the objective function. A GA was successfully implemented to improve the solution and provide better understanding and foundation of this scheduling problem. Feasible schedules of the initial population are created on permutation basis. Computational experiments of various genetic operators were attempted to improve performance of the algorithm. A lower bound of the objective value was introduced to reduce computational time and search region with the evolving generations.

Large-scale petroleum development projects involve long term commitment due to the considerable magnitude of investments. The study assumes that investment decisions are irreversible and selected project remains active throughout the planning horizon. The model does not permit partial development. A project staging case was investigated and showed a potential for improving the assets value and resources allocation.

The sequence and timing of selection of investment projects have pronounced effect on the financial performance of the assets. The proposed model permits all investment opportunities to compete equally for limited resources. Furthermore, the application of the proposed model offers a consistent planning workflow. The model provides the capability to analyze more scheduling alternatives in less time.

The rising prices of oil and gas expand the levels of activities in the industry. This requires improving management of various resources and their optimal allocation to expand production capacity and meet increasing energy demand. The proposed model can be utilized to thoroughly investigate the various resources and their effect on the assets value.

6.2 Future Research

The proposed model is limited to deterministic applications with limited sensitivity assessment. However, the uncertainties associated with oil prices and various reserves classes would require extension study to consider these uncertainties. The extension study of uncertainties will be challenging for large-scale instances due to the computational complexity of the multi-constraints problem in multiple periods.

Projects staging is another potential extension study. Partial development of large-scale petroleum development projects has the potential to improve selection decision of investments opportunities under resources constraints. This would create a discrete-continuous scheduling problem which involves further assumptions and more detailed analysis of various activities of individual projects.

NOMENCLATURE

B_i	Capital Budget
b_{ij}	Capital Costs
C_k	Penalty Sum
c_i	Knapsack Capacity
E	Expansion
e_{ij}	Efficiency
F_i	Offshore Rig-Year Level
f_{ij}	Offshore Rig-Year Required
m	Population Size
N	Number of Projects
n	Population Size
P	Project
p_{ij}	Knapsack Profit
Q_i	Target Production Rate
q_{ij}	Production Rate
R_i	Operating Budget
r_{ij}	Operating Costs
re	Relevance Value
S_i	Onshore Rig-Year Level

s	Onshore Rig-Year Required
T	Number of Periods
t	Time
w_{ij}	Knapsack Item Weight
x_{ij}	Binary Decision Variable
Z	Number of Constraints
z_{ij}	Time-Dependent Binary Decision Variable

Subscripts

i	Time Index
j	Projects Index
k	Schedules Index
z	Constraints Index

Abbreviations

AEO2007	Annual Energy Outlook 2007
B&B	Branch and Bound
CERA	Cambridge Energy Research Associates
CIR	Citi Investment Research
DP	Dynamic Programming

E&P	Exploration and Production
EIA	Energy Information Association
GA	Genetic Algorithm
KP	Knapsack Problems
LP	Linear Programming
MDKP	Multidimensional Knapsack Problems
MDMKP	Multidimensional Multiple Knapsack Problems
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Nonlinear Programming
MKP	Multiple Knapsack Problems
NPC	National Petroleum Council
NPV	Net Present Value
NPVI	Ratio of NPV to Investment
OPEC	Organization of the Petroleum Exporting Countries
RCPSP	Resource-Constrained Projects Scheduling Problems
SPE	Society of Petroleum Engineers
TSP	Traveling Salesman Problem
UN	United Nations

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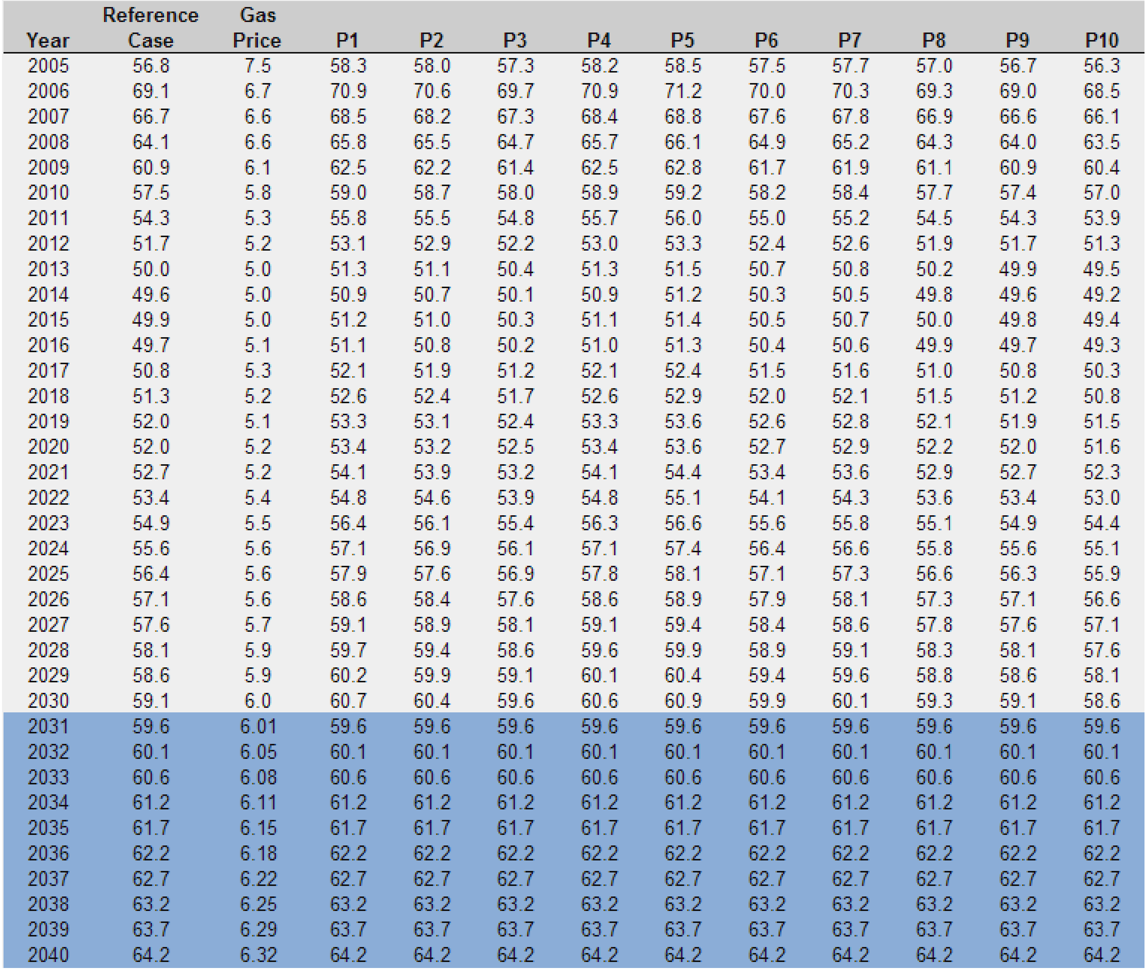
APPENDIX A

OIL AND GAS PRICES

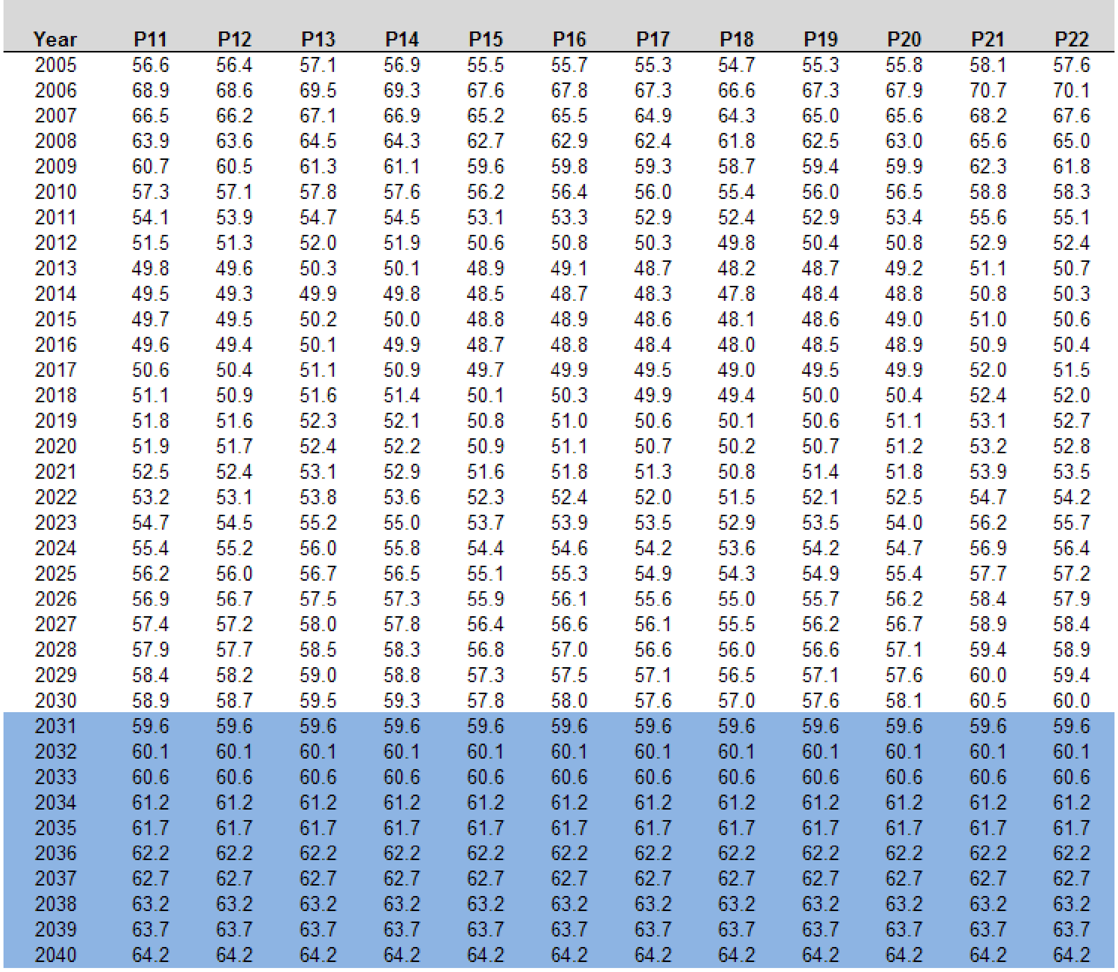
1. Reference Price Case for Development Projects P1 to P10



Year	Reference Case	Gas Price	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
2005	56.8	7.5	58.3	58.0	57.3	58.2	58.5	57.5	57.7	57.0	56.7	56.3
2006	69.1	6.7	70.9	70.6	69.7	70.9	71.2	70.0	70.3	69.3	69.0	68.5
2007	66.7	6.6	68.5	68.2	67.3	68.4	68.8	67.6	67.8	66.9	66.6	66.1
2008	64.1	6.6	65.8	65.5	64.7	65.7	66.1	64.9	65.2	64.3	64.0	63.5
2009	60.9	6.1	62.5	62.2	61.4	62.5	62.8	61.7	61.9	61.1	60.9	60.4
2010	57.5	5.8	59.0	58.7	58.0	58.9	59.2	58.2	58.4	57.7	57.4	57.0
2011	54.3	5.3	55.8	55.5	54.8	55.7	56.0	55.0	55.2	54.5	54.3	53.9
2012	51.7	5.2	53.1	52.9	52.2	53.0	53.3	52.4	52.6	51.9	51.7	51.3
2013	50.0	5.0	51.3	51.1	50.4	51.3	51.5	50.7	50.8	50.2	49.9	49.5
2014	49.6	5.0	50.9	50.7	50.1	50.9	51.2	50.3	50.5	49.8	49.6	49.2
2015	49.9	5.0	51.2	51.0	50.3	51.1	51.4	50.5	50.7	50.0	49.8	49.4
2016	49.7	5.1	51.1	50.8	50.2	51.0	51.3	50.4	50.6	49.9	49.7	49.3
2017	50.8	5.3	52.1	51.9	51.2	52.1	52.4	51.5	51.6	51.0	50.8	50.3
2018	51.3	5.2	52.6	52.4	51.7	52.6	52.9	52.0	52.1	51.5	51.2	50.8
2019	52.0	5.1	53.3	53.1	52.4	53.3	53.6	52.6	52.8	52.1	51.9	51.5
2020	52.0	5.2	53.4	53.2	52.5	53.4	53.6	52.7	52.9	52.2	52.0	51.6
2021	52.7	5.2	54.1	53.9	53.2	54.1	54.4	53.4	53.6	52.9	52.7	52.3
2022	53.4	5.4	54.8	54.6	53.9	54.8	55.1	54.1	54.3	53.6	53.4	53.0
2023	54.9	5.5	56.4	56.1	55.4	56.3	56.6	55.6	55.8	55.1	54.9	54.4
2024	55.6	5.6	57.1	56.9	56.1	57.1	57.4	56.4	56.6	55.8	55.6	55.1
2025	56.4	5.6	57.9	57.6	56.9	57.8	58.1	57.1	57.3	56.6	56.3	55.9
2026	57.1	5.6	58.6	58.4	57.6	58.6	58.9	57.9	58.1	57.3	57.1	56.6
2027	57.6	5.7	59.1	58.9	58.1	59.1	59.4	58.4	58.6	57.8	57.6	57.1
2028	58.1	5.9	59.7	59.4	58.6	59.6	59.9	58.9	59.1	58.3	58.1	57.6
2029	58.6	5.9	60.2	59.9	59.1	60.1	60.4	59.4	59.6	58.8	58.6	58.1
2030	59.1	6.0	60.7	60.4	59.6	60.6	60.9	59.9	60.1	59.3	59.1	58.6
2031	59.6	6.01	59.6	59.6	59.6	59.6	59.6	59.6	59.6	59.6	59.6	59.6
2032	60.1	6.05	60.1	60.1	60.1	60.1	60.1	60.1	60.1	60.1	60.1	60.1
2033	60.6	6.08	60.6	60.6	60.6	60.6	60.6	60.6	60.6	60.6	60.6	60.6
2034	61.2	6.11	61.2	61.2	61.2	61.2	61.2	61.2	61.2	61.2	61.2	61.2
2035	61.7	6.15	61.7	61.7	61.7	61.7	61.7	61.7	61.7	61.7	61.7	61.7
2036	62.2	6.18	62.2	62.2	62.2	62.2	62.2	62.2	62.2	62.2	62.2	62.2
2037	62.7	6.22	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7
2038	63.2	6.25	63.2	63.2	63.2	63.2	63.2	63.2	63.2	63.2	63.2	63.2
2039	63.7	6.29	63.7	63.7	63.7	63.7	63.7	63.7	63.7	63.7	63.7	63.7
2040	64.2	6.32	64.2	64.2	64.2	64.2	64.2	64.2	64.2	64.2	64.2	64.2

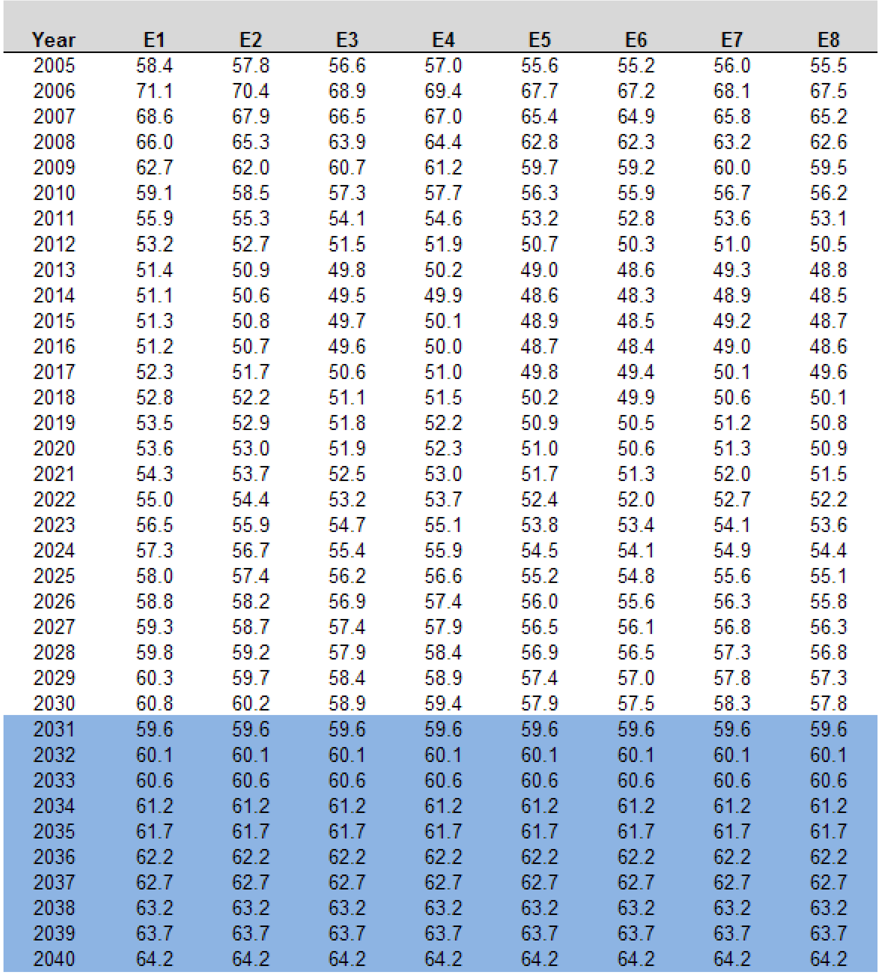
* Price projection by EIA, AEO2007. The shaded area is an extrapolation.

2. Reference Price Case for Development Projects P11 to P22



Year	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22
2005	56.6	56.4	57.1	56.9	55.5	55.7	55.3	54.7	55.3	55.8	58.1	57.6
2006	68.9	68.6	69.5	69.3	67.6	67.8	67.3	66.6	67.3	67.9	70.7	70.1
2007	66.5	66.2	67.1	66.9	65.2	65.5	64.9	64.3	65.0	65.6	68.2	67.6
2008	63.9	63.6	64.5	64.3	62.7	62.9	62.4	61.8	62.5	63.0	65.6	65.0
2009	60.7	60.5	61.3	61.1	59.6	59.8	59.3	58.7	59.4	59.9	62.3	61.8
2010	57.3	57.1	57.8	57.6	56.2	56.4	56.0	55.4	56.0	56.5	58.8	58.3
2011	54.1	53.9	54.7	54.5	53.1	53.3	52.9	52.4	52.9	53.4	55.6	55.1
2012	51.5	51.3	52.0	51.9	50.6	50.8	50.3	49.8	50.4	50.8	52.9	52.4
2013	49.8	49.6	50.3	50.1	48.9	49.1	48.7	48.2	48.7	49.2	51.1	50.7
2014	49.5	49.3	49.9	49.8	48.5	48.7	48.3	47.8	48.4	48.8	50.8	50.3
2015	49.7	49.5	50.2	50.0	48.8	48.9	48.6	48.1	48.6	49.0	51.0	50.6
2016	49.6	49.4	50.1	49.9	48.7	48.8	48.4	48.0	48.5	48.9	50.9	50.4
2017	50.6	50.4	51.1	50.9	49.7	49.9	49.5	49.0	49.5	49.9	52.0	51.5
2018	51.1	50.9	51.6	51.4	50.1	50.3	49.9	49.4	50.0	50.4	52.4	52.0
2019	51.8	51.6	52.3	52.1	50.8	51.0	50.6	50.1	50.6	51.1	53.1	52.7
2020	51.9	51.7	52.4	52.2	50.9	51.1	50.7	50.2	50.7	51.2	53.2	52.8
2021	52.5	52.4	53.1	52.9	51.6	51.8	51.3	50.8	51.4	51.8	53.9	53.5
2022	53.2	53.1	53.8	53.6	52.3	52.4	52.0	51.5	52.1	52.5	54.7	54.2
2023	54.7	54.5	55.2	55.0	53.7	53.9	53.5	52.9	53.5	54.0	56.2	55.7
2024	55.4	55.2	56.0	55.8	54.4	54.6	54.2	53.6	54.2	54.7	56.9	56.4
2025	56.2	56.0	56.7	56.5	55.1	55.3	54.9	54.3	54.9	55.4	57.7	57.2
2026	56.9	56.7	57.5	57.3	55.9	56.1	55.6	55.0	55.7	56.2	58.4	57.9
2027	57.4	57.2	58.0	57.8	56.4	56.6	56.1	55.5	56.2	56.7	58.9	58.4
2028	57.9	57.7	58.5	58.3	56.8	57.0	56.6	56.0	56.6	57.1	59.4	58.9
2029	58.4	58.2	59.0	58.8	57.3	57.5	57.1	56.5	57.1	57.6	60.0	59.4
2030	58.9	58.7	59.5	59.3	57.8	58.0	57.6	57.0	57.6	58.1	60.5	60.0
2031	59.6	59.6	59.6	59.6	59.6	59.6	59.6	59.6	59.6	59.6	59.6	59.6
2032	60.1	60.1	60.1	60.1	60.1	60.1	60.1	60.1	60.1	60.1	60.1	60.1
2033	60.6	60.6	60.6	60.6	60.6	60.6	60.6	60.6	60.6	60.6	60.6	60.6
2034	61.2	61.2	61.2	61.2	61.2	61.2	61.2	61.2	61.2	61.2	61.2	61.2
2035	61.7	61.7	61.7	61.7	61.7	61.7	61.7	61.7	61.7	61.7	61.7	61.7
2036	62.2	62.2	62.2	62.2	62.2	62.2	62.2	62.2	62.2	62.2	62.2	62.2
2037	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7
2038	63.2	63.2	63.2	63.2	63.2	63.2	63.2	63.2	63.2	63.2	63.2	63.2
2039	63.7	63.7	63.7	63.7	63.7	63.7	63.7	63.7	63.7	63.7	63.7	63.7
2040	64.2	64.2	64.2	64.2	64.2	64.2	64.2	64.2	64.2	64.2	64.2	64.2

3. Reference Price Case for Expansion Projects E1 to E8

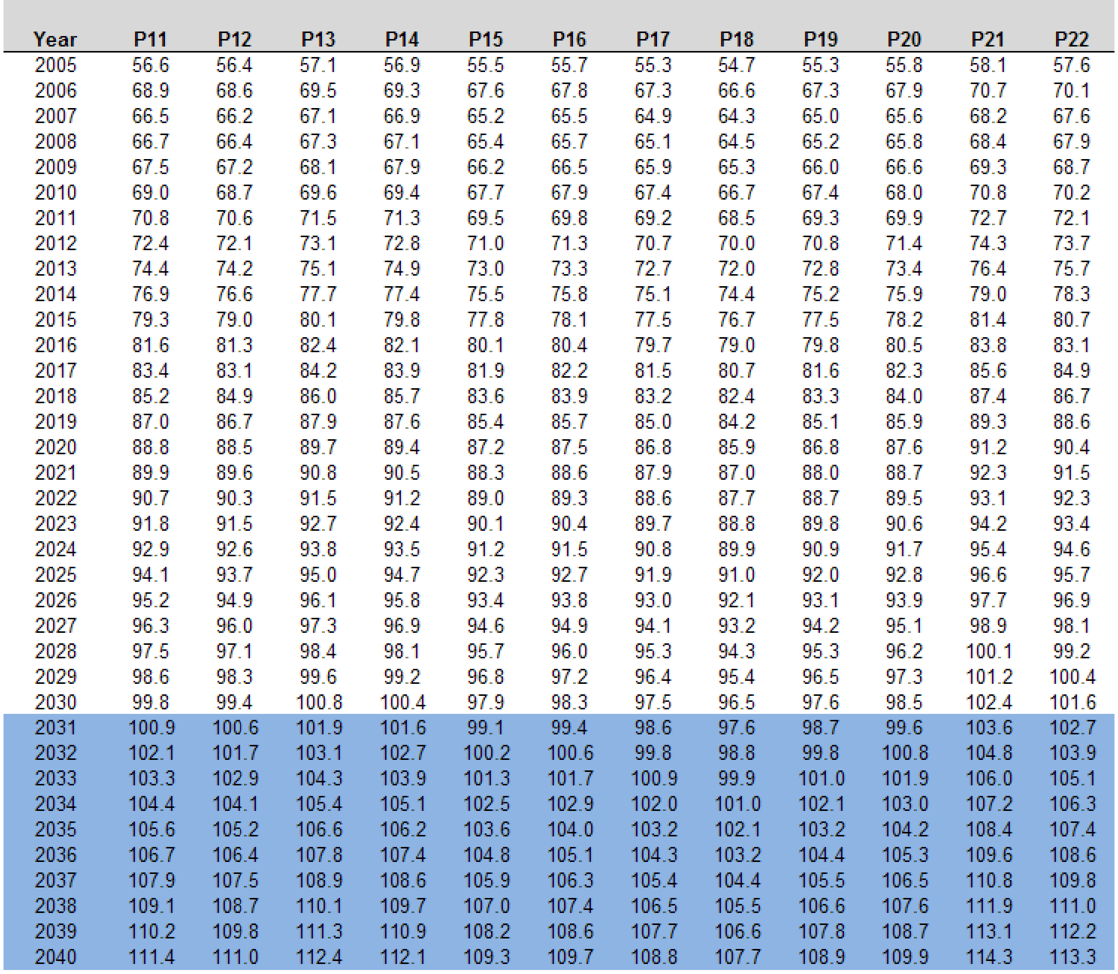


Year	E1	E2	E3	E4	E5	E6	E7	E8
2005	58.4	57.8	56.6	57.0	55.6	55.2	56.0	55.5
2006	71.1	70.4	68.9	69.4	67.7	67.2	68.1	67.5
2007	68.6	67.9	66.5	67.0	65.4	64.9	65.8	65.2
2008	66.0	65.3	63.9	64.4	62.8	62.3	63.2	62.6
2009	62.7	62.0	60.7	61.2	59.7	59.2	60.0	59.5
2010	59.1	58.5	57.3	57.7	56.3	55.9	56.7	56.2
2011	55.9	55.3	54.1	54.6	53.2	52.8	53.6	53.1
2012	53.2	52.7	51.5	51.9	50.7	50.3	51.0	50.5
2013	51.4	50.9	49.8	50.2	49.0	48.6	49.3	48.8
2014	51.1	50.6	49.5	49.9	48.6	48.3	48.9	48.5
2015	51.3	50.8	49.7	50.1	48.9	48.5	49.2	48.7
2016	51.2	50.7	49.6	50.0	48.7	48.4	49.0	48.6
2017	52.3	51.7	50.6	51.0	49.8	49.4	50.1	49.6
2018	52.8	52.2	51.1	51.5	50.2	49.9	50.6	50.1
2019	53.5	52.9	51.8	52.2	50.9	50.5	51.2	50.8
2020	53.6	53.0	51.9	52.3	51.0	50.6	51.3	50.9
2021	54.3	53.7	52.5	53.0	51.7	51.3	52.0	51.5
2022	55.0	54.4	53.2	53.7	52.4	52.0	52.7	52.2
2023	56.5	55.9	54.7	55.1	53.8	53.4	54.1	53.6
2024	57.3	56.7	55.4	55.9	54.5	54.1	54.9	54.4
2025	58.0	57.4	56.2	56.6	55.2	54.8	55.6	55.1
2026	58.8	58.2	56.9	57.4	56.0	55.6	56.3	55.8
2027	59.3	58.7	57.4	57.9	56.5	56.1	56.8	56.3
2028	59.8	59.2	57.9	58.4	56.9	56.5	57.3	56.8
2029	60.3	59.7	58.4	58.9	57.4	57.0	57.8	57.3
2030	60.8	60.2	58.9	59.4	57.9	57.5	58.3	57.8
2031	59.6	59.6	59.6	59.6	59.6	59.6	59.6	59.6
2032	60.1	60.1	60.1	60.1	60.1	60.1	60.1	60.1
2033	60.6	60.6	60.6	60.6	60.6	60.6	60.6	60.6
2034	61.2	61.2	61.2	61.2	61.2	61.2	61.2	61.2
2035	61.7	61.7	61.7	61.7	61.7	61.7	61.7	61.7
2036	62.2	62.2	62.2	62.2	62.2	62.2	62.2	62.2
2037	62.7	62.7	62.7	62.7	62.7	62.7	62.7	62.7
2038	63.2	63.2	63.2	63.2	63.2	63.2	63.2	63.2
2039	63.7	63.7	63.7	63.7	63.7	63.7	63.7	63.7
2040	64.2	64.2	64.2	64.2	64.2	64.2	64.2	64.2

4. High Price Case for Development Projects P1 to P10

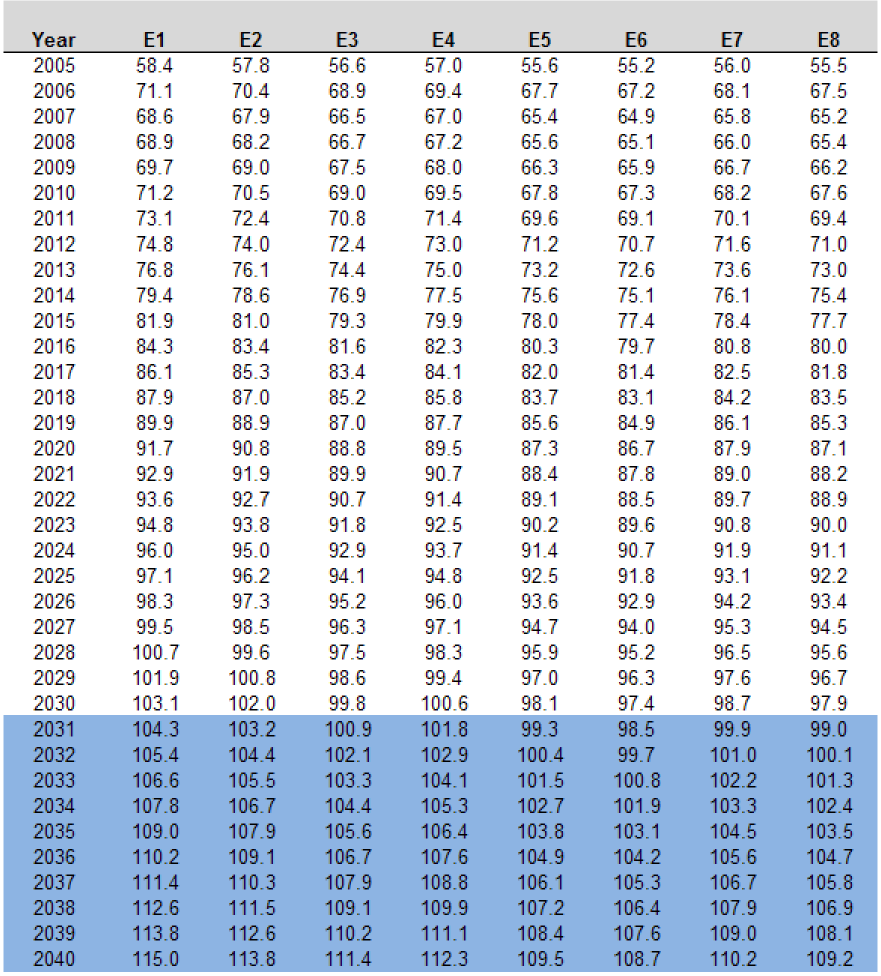
Year	Reference Case	Gas Price	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
2005	56.8	7.5	58.3	58.0	57.3	58.2	58.5	57.5	57.7	57.0	56.7	56.3
2006	69.1	6.7	70.9	70.6	69.7	70.9	71.2	70.0	70.3	69.3	69.0	68.5
2007	66.7	6.7	68.5	68.2	67.3	68.4	68.8	67.6	67.8	66.9	66.6	66.1
2008	66.9	6.9	68.7	68.4	67.5	68.6	69.0	67.8	68.0	67.1	66.9	66.3
2009	67.7	6.6	69.5	69.2	68.3	69.4	69.8	68.6	68.8	67.9	67.6	67.1
2010	69.2	6.3	71.0	70.7	69.8	71.0	71.3	70.1	70.4	69.5	69.1	68.6
2011	71.1	6.2	73.0	72.6	71.7	72.9	73.3	72.0	72.3	71.3	71.0	70.5
2012	72.6	5.8	74.6	74.2	73.3	74.5	74.9	73.6	73.9	72.9	72.6	72.0
2013	74.7	5.8	76.7	76.3	75.3	76.6	77.0	75.7	75.9	74.9	74.6	74.0
2014	77.2	5.8	79.2	78.9	77.9	79.2	79.6	78.2	78.5	77.5	77.1	76.5
2015	79.6	5.8	81.7	81.3	80.3	81.6	82.0	80.6	80.9	79.8	79.5	78.9
2016	81.9	6.0	84.1	83.7	82.6	84.0	84.4	83.0	83.3	82.2	81.8	81.2
2017	83.7	6.2	85.9	85.5	84.4	85.8	86.3	84.8	85.1	84.0	83.6	83.0
2018	85.5	6.0	87.7	87.3	86.2	87.6	88.1	86.6	86.9	85.8	85.4	84.7
2019	87.3	5.7	89.6	89.2	88.1	89.6	90.0	88.5	88.8	87.6	87.2	86.6
2020	89.1	5.9	91.5	91.1	89.9	91.4	91.9	90.3	90.6	89.4	89.0	88.3
2021	90.3	6.2	92.6	92.2	91.1	92.6	93.0	91.5	91.8	90.6	90.2	89.5
2022	91.0	6.3	93.4	93.0	91.8	93.3	93.8	92.2	92.5	91.3	90.9	90.2
2023	92.1	6.5	94.6	94.1	92.9	94.5	95.0	93.3	93.7	92.4	92.0	91.3
2024	93.3	6.6	95.7	95.3	94.1	95.6	96.1	94.5	94.8	93.6	93.2	92.4
2025	94.4	6.7	96.9	96.5	95.2	96.8	97.3	95.7	96.0	94.7	94.3	93.6
2026	95.5	6.9	98.1	97.7	96.4	98.0	98.5	96.8	97.1	95.9	95.5	94.7
2027	96.7	7.1	99.2	98.8	97.5	99.2	99.7	98.0	98.3	97.0	96.6	95.8
2028	97.8	7.3	100.4	100.0	98.7	100.3	100.9	99.1	99.5	98.2	97.8	97.0
2029	99.0	7.4	101.6	101.2	99.9	101.5	102.0	100.3	100.6	99.3	98.9	98.1
2030	100.1	7.6	102.8	102.3	101.0	102.7	103.2	101.5	101.8	100.5	100.1	99.3
2031	101.3	7.8	104.0	103.5	102.2	103.9	104.4	102.6	103.0	101.7	101.2	100.4
2032	102.5	8.1	105.2	104.7	103.4	105.1	105.6	103.8	104.2	102.8	102.4	101.6
2033	103.6	8.3	106.4	105.9	104.5	106.3	106.8	105.0	105.4	104.0	103.5	102.7
2034	104.8	8.5	107.6	107.1	105.7	107.5	108.0	106.2	106.5	105.2	104.7	103.9
2035	106.0	8.7	108.8	108.3	106.9	108.7	109.2	107.4	107.7	106.3	105.9	105.0
2036	107.1	8.9	109.9	109.5	108.1	109.8	110.4	108.5	108.9	107.5	107.0	106.2
2037	108.3	9.1	111.1	110.7	109.2	111.0	111.6	109.7	110.1	108.7	108.2	107.3
2038	109.4	9.3	112.3	111.8	110.4	112.2	112.8	110.9	111.3	109.8	109.3	108.5
2039	110.6	9.6	113.5	113.0	111.6	113.4	114.0	112.1	112.4	111.0	110.5	109.6
2040	111.8	9.8	114.7	114.2	112.7	114.6	115.2	113.2	113.6	112.2	111.7	110.8

5. High Price Case for Development Projects P11 to P22



Year	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22
2005	56.6	56.4	57.1	56.9	55.5	55.7	55.3	54.7	55.3	55.8	58.1	57.6
2006	68.9	68.6	69.5	69.3	67.6	67.8	67.3	66.6	67.3	67.9	70.7	70.1
2007	66.5	66.2	67.1	66.9	65.2	65.5	64.9	64.3	65.0	65.6	68.2	67.6
2008	66.7	66.4	67.3	67.1	65.4	65.7	65.1	64.5	65.2	65.8	68.4	67.9
2009	67.5	67.2	68.1	67.9	66.2	66.5	65.9	65.3	66.0	66.6	69.3	68.7
2010	69.0	68.7	69.6	69.4	67.7	67.9	67.4	66.7	67.4	68.0	70.8	70.2
2011	70.8	70.6	71.5	71.3	69.5	69.8	69.2	68.5	69.3	69.9	72.7	72.1
2012	72.4	72.1	73.1	72.8	71.0	71.3	70.7	70.0	70.8	71.4	74.3	73.7
2013	74.4	74.2	75.1	74.9	73.0	73.3	72.7	72.0	72.8	73.4	76.4	75.7
2014	76.9	76.6	77.7	77.4	75.5	75.8	75.1	74.4	75.2	75.9	79.0	78.3
2015	79.3	79.0	80.1	79.8	77.8	78.1	77.5	76.7	77.5	78.2	81.4	80.7
2016	81.6	81.3	82.4	82.1	80.1	80.4	79.7	79.0	79.8	80.5	83.8	83.1
2017	83.4	83.1	84.2	83.9	81.9	82.2	81.5	80.7	81.6	82.3	85.6	84.9
2018	85.2	84.9	86.0	85.7	83.6	83.9	83.2	82.4	83.3	84.0	87.4	86.7
2019	87.0	86.7	87.9	87.6	85.4	85.7	85.0	84.2	85.1	85.9	89.3	88.6
2020	88.8	88.5	89.7	89.4	87.2	87.5	86.8	85.9	86.8	87.6	91.2	90.4
2021	89.9	89.6	90.8	90.5	88.3	88.6	87.9	87.0	88.0	88.7	92.3	91.5
2022	90.7	90.3	91.5	91.2	89.0	89.3	88.6	87.7	88.7	89.5	93.1	92.3
2023	91.8	91.5	92.7	92.4	90.1	90.4	89.7	88.8	89.8	90.6	94.2	93.4
2024	92.9	92.6	93.8	93.5	91.2	91.5	90.8	89.9	90.9	91.7	95.4	94.6
2025	94.1	93.7	95.0	94.7	92.3	92.7	91.9	91.0	92.0	92.8	96.6	95.7
2026	95.2	94.9	96.1	95.8	93.4	93.8	93.0	92.1	93.1	93.9	97.7	96.9
2027	96.3	96.0	97.3	96.9	94.6	94.9	94.1	93.2	94.2	95.1	98.9	98.1
2028	97.5	97.1	98.4	98.1	95.7	96.0	95.3	94.3	95.3	96.2	100.1	99.2
2029	98.6	98.3	99.6	99.2	96.8	97.2	96.4	95.4	96.5	97.3	101.2	100.4
2030	99.8	99.4	100.8	100.4	97.9	98.3	97.5	96.5	97.6	98.5	102.4	101.6
2031	100.9	100.6	101.9	101.6	99.1	99.4	98.6	97.6	98.7	99.6	103.6	102.7
2032	102.1	101.7	103.1	102.7	100.2	100.6	99.8	98.8	99.8	100.8	104.8	103.9
2033	103.3	102.9	104.3	103.9	101.3	101.7	100.9	99.9	101.0	101.9	106.0	105.1
2034	104.4	104.1	105.4	105.1	102.5	102.9	102.0	101.0	102.1	103.0	107.2	106.3
2035	105.6	105.2	106.6	106.2	103.6	104.0	103.2	102.1	103.2	104.2	108.4	107.4
2036	106.7	106.4	107.8	107.4	104.8	105.1	104.3	103.2	104.4	105.3	109.6	108.6
2037	107.9	107.5	108.9	108.6	105.9	106.3	105.4	104.4	105.5	106.5	110.8	109.8
2038	109.1	108.7	110.1	109.7	107.0	107.4	106.5	105.5	106.6	107.6	111.9	111.0
2039	110.2	109.8	111.3	110.9	108.2	108.6	107.7	106.6	107.8	108.7	113.1	112.2
2040	111.4	111.0	112.4	112.1	109.3	109.7	108.8	107.7	108.9	109.9	114.3	113.3

6. **High Price Case for Expansion Projects E1 to E8**

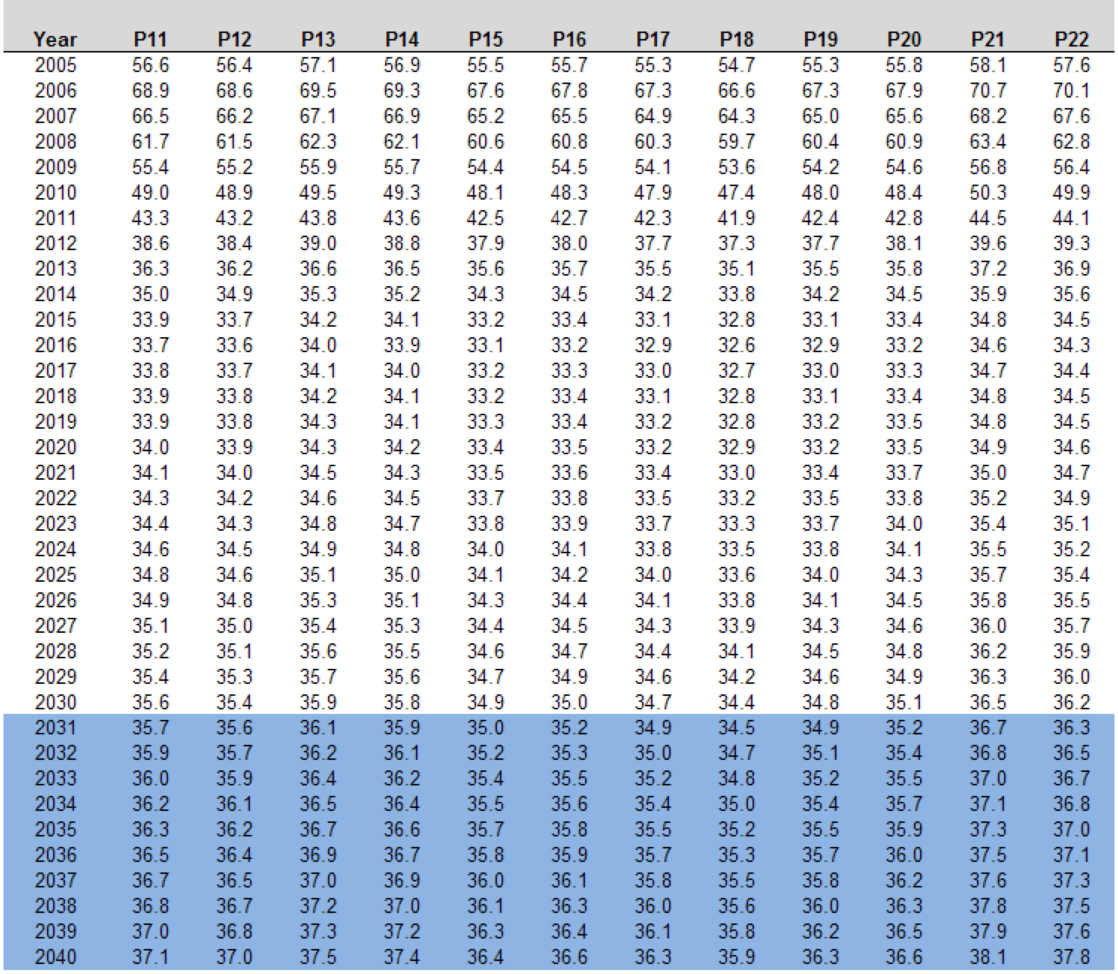


Year	E1	E2	E3	E4	E5	E6	E7	E8
2005	58.4	57.8	56.6	57.0	55.6	55.2	56.0	55.5
2006	71.1	70.4	68.9	69.4	67.7	67.2	68.1	67.5
2007	68.6	67.9	66.5	67.0	65.4	64.9	65.8	65.2
2008	68.9	68.2	66.7	67.2	65.6	65.1	66.0	65.4
2009	69.7	69.0	67.5	68.0	66.3	65.9	66.7	66.2
2010	71.2	70.5	69.0	69.5	67.8	67.3	68.2	67.6
2011	73.1	72.4	70.8	71.4	69.6	69.1	70.1	69.4
2012	74.8	74.0	72.4	73.0	71.2	70.7	71.6	71.0
2013	76.8	76.1	74.4	75.0	73.2	72.6	73.6	73.0
2014	79.4	78.6	76.9	77.5	75.6	75.1	76.1	75.4
2015	81.9	81.0	79.3	79.9	78.0	77.4	78.4	77.7
2016	84.3	83.4	81.6	82.3	80.3	79.7	80.8	80.0
2017	86.1	85.3	83.4	84.1	82.0	81.4	82.5	81.8
2018	87.9	87.0	85.2	85.8	83.7	83.1	84.2	83.5
2019	89.9	88.9	87.0	87.7	85.6	84.9	86.1	85.3
2020	91.7	90.8	88.8	89.5	87.3	86.7	87.9	87.1
2021	92.9	91.9	89.9	90.7	88.4	87.8	89.0	88.2
2022	93.6	92.7	90.7	91.4	89.1	88.5	89.7	88.9
2023	94.8	93.8	91.8	92.5	90.2	89.6	90.8	90.0
2024	96.0	95.0	92.9	93.7	91.4	90.7	91.9	91.1
2025	97.1	96.2	94.1	94.8	92.5	91.8	93.1	92.2
2026	98.3	97.3	95.2	96.0	93.6	92.9	94.2	93.4
2027	99.5	98.5	96.3	97.1	94.7	94.0	95.3	94.5
2028	100.7	99.6	97.5	98.3	95.9	95.2	96.5	95.6
2029	101.9	100.8	98.6	99.4	97.0	96.3	97.6	96.7
2030	103.1	102.0	99.8	100.6	98.1	97.4	98.7	97.9
2031	104.3	103.2	100.9	101.8	99.3	98.5	99.9	99.0
2032	105.4	104.4	102.1	102.9	100.4	99.7	101.0	100.1
2033	106.6	105.5	103.3	104.1	101.5	100.8	102.2	101.3
2034	107.8	106.7	104.4	105.3	102.7	101.9	103.3	102.4
2035	109.0	107.9	105.6	106.4	103.8	103.1	104.5	103.5
2036	110.2	109.1	106.7	107.6	104.9	104.2	105.6	104.7
2037	111.4	110.3	107.9	108.8	106.1	105.3	106.7	105.8
2038	112.6	111.5	109.1	109.9	107.2	106.4	107.9	106.9
2039	113.8	112.6	110.2	111.1	108.4	107.6	109.0	108.1
2040	115.0	113.8	111.4	112.3	109.5	108.7	110.2	109.2

7. Low Price Case for Development Projects P1 to P10

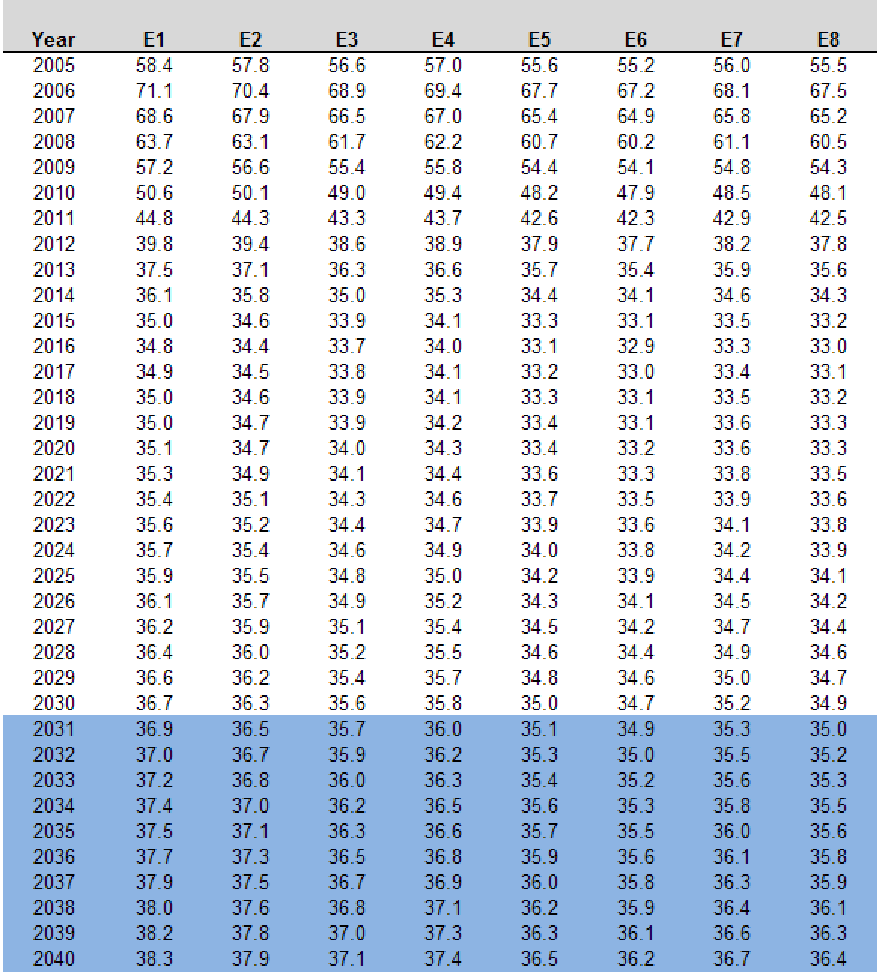
Year	Reference Case	Gas Price	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
2005	56.8	7.5	58.3	58.0	57.3	58.2	58.5	57.5	57.7	57.0	56.7	56.3
2006	69.1	6.7	70.9	70.6	69.7	70.9	71.2	70.0	70.3	69.3	69.0	68.5
2007	66.7	6.4	68.5	68.2	67.3	68.4	68.8	67.6	67.8	66.9	66.6	66.1
2008	61.9	6.3	63.6	63.3	62.5	63.5	63.8	62.8	63.0	62.2	61.9	61.4
2009	55.6	5.6	57.0	56.8	56.1	57.0	57.3	56.3	56.5	55.8	55.5	55.1
2010	49.2	5.1	50.5	50.3	49.6	50.5	50.7	49.9	50.0	49.4	49.2	48.8
2011	43.5	4.8	44.6	44.4	43.9	44.6	44.8	44.1	44.2	43.6	43.4	43.1
2012	38.7	4.4	39.7	39.6	39.1	39.7	39.9	39.2	39.4	38.9	38.7	38.4
2013	36.4	4.2	37.4	37.2	36.7	37.3	37.5	36.9	37.0	36.5	36.4	36.1
2014	35.1	4.1	36.0	35.9	35.4	36.0	36.2	35.6	35.7	35.2	35.1	34.8
2015	34.0	4.0	34.9	34.7	34.3	34.9	35.0	34.4	34.6	34.1	34.0	33.7
2016	33.8	4.1	34.7	34.6	34.1	34.7	34.9	34.3	34.4	33.9	33.8	33.5
2017	33.9	4.2	34.8	34.6	34.2	34.8	34.9	34.4	34.5	34.0	33.9	33.6
2018	34.0	4.2	34.9	34.7	34.3	34.9	35.0	34.4	34.6	34.1	34.0	33.7
2019	34.1	4.2	35.0	34.8	34.4	34.9	35.1	34.5	34.6	34.2	34.0	33.8
2020	34.1	4.2	35.0	34.9	34.4	35.0	35.2	34.6	34.7	34.2	34.1	33.8
2021	34.3	4.4	35.2	35.0	34.6	35.1	35.3	34.7	34.8	34.4	34.2	34.0
2022	34.4	4.6	35.3	35.2	34.7	35.3	35.5	34.9	35.0	34.5	34.4	34.1
2023	34.6	4.6	35.5	35.3	34.9	35.5	35.6	35.0	35.1	34.7	34.5	34.3
2024	34.7	4.8	35.6	35.5	35.0	35.6	35.8	35.2	35.3	34.8	34.7	34.4
2025	34.9	4.7	35.8	35.7	35.2	35.8	36.0	35.3	35.5	35.0	34.9	34.6
2026	35.0	4.9	36.0	35.8	35.4	35.9	36.1	35.5	35.6	35.2	35.0	34.7
2027	35.2	4.9	36.1	36.0	35.5	36.1	36.3	35.7	35.8	35.3	35.2	34.9
2028	35.4	5.0	36.3	36.1	35.7	36.3	36.5	35.8	36.0	35.5	35.3	35.1
2029	35.5	5.0	36.5	36.3	35.8	36.4	36.6	36.0	36.1	35.6	35.5	35.2
2030	35.7	5.1	36.6	36.5	36.0	36.6	36.8	36.2	36.3	35.8	35.6	35.4
2031	35.8	5.1	36.8	36.6	36.2	36.8	36.9	36.3	36.4	36.0	35.8	35.5
2032	36.0	5.2	36.9	36.8	36.3	36.9	37.1	36.5	36.6	36.1	36.0	35.7
2033	36.2	5.2	37.1	37.0	36.5	37.1	37.3	36.6	36.8	36.3	36.1	35.8
2034	36.3	5.3	37.3	37.1	36.6	37.2	37.4	36.8	36.9	36.4	36.3	36.0
2035	36.5	5.3	37.4	37.3	36.8	37.4	37.6	37.0	37.1	36.6	36.4	36.1
2036	36.6	5.4	37.6	37.4	36.9	37.6	37.8	37.1	37.2	36.8	36.6	36.3
2037	36.8	5.5	37.8	37.6	37.1	37.7	37.9	37.3	37.4	36.9	36.8	36.5
2038	36.9	5.5	37.9	37.8	37.3	37.9	38.1	37.4	37.6	37.1	36.9	36.6
2039	37.1	5.6	38.1	37.9	37.4	38.0	38.2	37.6	37.7	37.2	37.1	36.8
2040	37.3	5.6	38.2	38.1	37.6	38.2	38.4	37.7	37.9	37.4	37.2	36.9

8. Low Price Case for Development Projects P11 to P22



Year	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22
2005	56.6	56.4	57.1	56.9	55.5	55.7	55.3	54.7	55.3	55.8	58.1	57.6
2006	68.9	68.6	69.5	69.3	67.6	67.8	67.3	66.6	67.3	67.9	70.7	70.1
2007	66.5	66.2	67.1	66.9	65.2	65.5	64.9	64.3	65.0	65.6	68.2	67.6
2008	61.7	61.5	62.3	62.1	60.6	60.8	60.3	59.7	60.4	60.9	63.4	62.8
2009	55.4	55.2	55.9	55.7	54.4	54.5	54.1	53.6	54.2	54.6	56.8	56.4
2010	49.0	48.9	49.5	49.3	48.1	48.3	47.9	47.4	48.0	48.4	50.3	49.9
2011	43.3	43.2	43.8	43.6	42.5	42.7	42.3	41.9	42.4	42.8	44.5	44.1
2012	38.6	38.4	39.0	38.8	37.9	38.0	37.7	37.3	37.7	38.1	39.6	39.3
2013	36.3	36.2	36.6	36.5	35.6	35.7	35.5	35.1	35.5	35.8	37.2	36.9
2014	35.0	34.9	35.3	35.2	34.3	34.5	34.2	33.8	34.2	34.5	35.9	35.6
2015	33.9	33.7	34.2	34.1	33.2	33.4	33.1	32.8	33.1	33.4	34.8	34.5
2016	33.7	33.6	34.0	33.9	33.1	33.2	32.9	32.6	32.9	33.2	34.6	34.3
2017	33.8	33.7	34.1	34.0	33.2	33.3	33.0	32.7	33.0	33.3	34.7	34.4
2018	33.9	33.8	34.2	34.1	33.2	33.4	33.1	32.8	33.1	33.4	34.8	34.5
2019	33.9	33.8	34.3	34.1	33.3	33.4	33.2	32.8	33.2	33.5	34.8	34.5
2020	34.0	33.9	34.3	34.2	33.4	33.5	33.2	32.9	33.2	33.5	34.9	34.6
2021	34.1	34.0	34.5	34.3	33.5	33.6	33.4	33.0	33.4	33.7	35.0	34.7
2022	34.3	34.2	34.6	34.5	33.7	33.8	33.5	33.2	33.5	33.8	35.2	34.9
2023	34.4	34.3	34.8	34.7	33.8	33.9	33.7	33.3	33.7	34.0	35.4	35.1
2024	34.6	34.5	34.9	34.8	34.0	34.1	33.8	33.5	33.8	34.1	35.5	35.2
2025	34.8	34.6	35.1	35.0	34.1	34.2	34.0	33.6	34.0	34.3	35.7	35.4
2026	34.9	34.8	35.3	35.1	34.3	34.4	34.1	33.8	34.1	34.5	35.8	35.5
2027	35.1	35.0	35.4	35.3	34.4	34.5	34.3	33.9	34.3	34.6	36.0	35.7
2028	35.2	35.1	35.6	35.5	34.6	34.7	34.4	34.1	34.5	34.8	36.2	35.9
2029	35.4	35.3	35.7	35.6	34.7	34.9	34.6	34.2	34.6	34.9	36.3	36.0
2030	35.6	35.4	35.9	35.8	34.9	35.0	34.7	34.4	34.8	35.1	36.5	36.2
2031	35.7	35.6	36.1	35.9	35.0	35.2	34.9	34.5	34.9	35.2	36.7	36.3
2032	35.9	35.7	36.2	36.1	35.2	35.3	35.0	34.7	35.1	35.4	36.8	36.5
2033	36.0	35.9	36.4	36.2	35.4	35.5	35.2	34.8	35.2	35.5	37.0	36.7
2034	36.2	36.1	36.5	36.4	35.5	35.6	35.4	35.0	35.4	35.7	37.1	36.8
2035	36.3	36.2	36.7	36.6	35.7	35.8	35.5	35.2	35.5	35.9	37.3	37.0
2036	36.5	36.4	36.9	36.7	35.8	35.9	35.7	35.3	35.7	36.0	37.5	37.1
2037	36.7	36.5	37.0	36.9	36.0	36.1	35.8	35.5	35.8	36.2	37.6	37.3
2038	36.8	36.7	37.2	37.0	36.1	36.3	36.0	35.6	36.0	36.3	37.8	37.5
2039	37.0	36.8	37.3	37.2	36.3	36.4	36.1	35.8	36.2	36.5	37.9	37.6
2040	37.1	37.0	37.5	37.4	36.4	36.6	36.3	35.9	36.3	36.6	38.1	37.8

9. Low Price Case for Expansion Projects E1 to E8



Year	E1	E2	E3	E4	E5	E6	E7	E8
2005	58.4	57.8	56.6	57.0	55.6	55.2	56.0	55.5
2006	71.1	70.4	68.9	69.4	67.7	67.2	68.1	67.5
2007	68.6	67.9	66.5	67.0	65.4	64.9	65.8	65.2
2008	63.7	63.1	61.7	62.2	60.7	60.2	61.1	60.5
2009	57.2	56.6	55.4	55.8	54.4	54.1	54.8	54.3
2010	50.6	50.1	49.0	49.4	48.2	47.9	48.5	48.1
2011	44.8	44.3	43.3	43.7	42.6	42.3	42.9	42.5
2012	39.8	39.4	38.6	38.9	37.9	37.7	38.2	37.8
2013	37.5	37.1	36.3	36.6	35.7	35.4	35.9	35.6
2014	36.1	35.8	35.0	35.3	34.4	34.1	34.6	34.3
2015	35.0	34.6	33.9	34.1	33.3	33.1	33.5	33.2
2016	34.8	34.4	33.7	34.0	33.1	32.9	33.3	33.0
2017	34.9	34.5	33.8	34.1	33.2	33.0	33.4	33.1
2018	35.0	34.6	33.9	34.1	33.3	33.1	33.5	33.2
2019	35.0	34.7	33.9	34.2	33.4	33.1	33.6	33.3
2020	35.1	34.7	34.0	34.3	33.4	33.2	33.6	33.3
2021	35.3	34.9	34.1	34.4	33.6	33.3	33.8	33.5
2022	35.4	35.1	34.3	34.6	33.7	33.5	33.9	33.6
2023	35.6	35.2	34.4	34.7	33.9	33.6	34.1	33.8
2024	35.7	35.4	34.6	34.9	34.0	33.8	34.2	33.9
2025	35.9	35.5	34.8	35.0	34.2	33.9	34.4	34.1
2026	36.1	35.7	34.9	35.2	34.3	34.1	34.5	34.2
2027	36.2	35.9	35.1	35.4	34.5	34.2	34.7	34.4
2028	36.4	36.0	35.2	35.5	34.6	34.4	34.9	34.6
2029	36.6	36.2	35.4	35.7	34.8	34.6	35.0	34.7
2030	36.7	36.3	35.6	35.8	35.0	34.7	35.2	34.9
2031	36.9	36.5	35.7	36.0	35.1	34.9	35.3	35.0
2032	37.0	36.7	35.9	36.2	35.3	35.0	35.5	35.2
2033	37.2	36.8	36.0	36.3	35.4	35.2	35.6	35.3
2034	37.4	37.0	36.2	36.5	35.6	35.3	35.8	35.5
2035	37.5	37.1	36.3	36.6	35.7	35.5	36.0	35.6
2036	37.7	37.3	36.5	36.8	35.9	35.6	36.1	35.8
2037	37.9	37.5	36.7	36.9	36.0	35.8	36.3	35.9
2038	38.0	37.6	36.8	37.1	36.2	35.9	36.4	36.1
2039	38.2	37.8	37.0	37.3	36.3	36.1	36.6	36.3
2040	38.3	37.9	37.1	37.4	36.5	36.2	36.7	36.4

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