THE OPTIMIZATION OF ENERGY PORTFOLIO MANAGEMENT (EPM): FRAMEWORK AND SIMULATION

Presented
By

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Abstract

With the rapid increasing energy needs from all kinds of energy consumers, energy prices have increased dramatically, especially the price for fossil energy. How to lower energy consumption cost, which energy is optimal choice, and how social costs of energy will impact on energy consumption, these questions are addressed in this dissertation via Energy Portfolio Management (EPM) model with framework and simulation.

The EPM model is established to find out an optimal energy solution which can provide useful guidance to energy consumers and policymakers about how to select optimal energy portfolio with lower cost and less risk. The conceptual framework presents the methodology of EPM, while EPM simulations demonstrate the selection of optimal energy choices, and further, the impacts of social cost on the optimal energy portfolio in the case of United States.

The findings from EPM Simulations fall into three categories: 1)without considering social cost, biomass and coal are optimal choices and should consume at the maximum; 2)considering single social cost, coal and nuclear are favored only if social cost of coal is less than 100% of its private cost or social cost of nuclear is less than 300% of its private cost, otherwise, biomass is optimal; 3)considering all sorts of social costs simultaneously, optimal energy portfolio varies with the level of social cost: with low and central level of social cost, coal and nuclear are preferable due to their stable and lower cost; with high level of social cost, biomass, nuclear and potential natural gas are still favored, however the optimal solution will switch to favor biomass (if social cost of coal is more than 300% of its private cost or social cost of nuclear is 830% more than its private cost.

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Chapter 1 Introduction

Energy, as necessary human-usable natural resources, has been discussed for many years; most researches and discussions focus on two general categories: energy efficiency and renewable energy. In the current researches, energy efficiency has been widely discussed as an efficient way of improving energy saving and consumption, and also has been applied to many industries. Energy alternatives, such as renewable energy, are becoming more and more important topic in recent years to respond to the environmental and social worries from the consumption of traditional energy.

As the dramatic increase of conventional oil price, energy consumers are paying more and more on the energy consumption, not only for the cost of energy on production, operation and maintenance of energy, but also for the social costs coming with energy, various taxes for instance. Also the voices from the worries about the environmental and social impacts are drawing more and more attention, renewable energy resources becomes more cost competitive compared to traditional energy. All of these facts will finally change or switch the energy consumption structure in the future; but how and when it will happen is not known. Therefore, this dissertation attempts to develop a conceptual model (called Energy Portfolio Management model, referred to EPM in the following pages) which can provide the framework for energy consumption management and an optimal combination with lower energy cost and less associated risk for energy consumers.

Portfolio management is a term that has been mostly used in the financial field to determine the optimal portfolio strategy for investment; and has been used in this dissertation as a way of managing the overall energy consumption, in order to optimize the energy consumption and saving for energy consumers. EPM model is developed based on the mean-variance portfolio theory and the optimization techniques. The main purpose of this dissertation is to establish a conceptual EPM framework to provide an optimal energy consumption solution with the available energy resources and energy social cost structure, and to simulate EPM model using optimization techniques.

The dissertation has seven chapters, starts with the introduction, research objectives and literature review chapters followed by EPM conceptual model and simulation chapters, and ends with conclusion chapter. Chapter Three examines all the current topics and theories about the energy resources and consumptions, for example, the current production and consumption of energy resources, the debate regarding the peak oil and theory, portfolio theory and mean-variance theory and applications. All of these literatures are constructed together to develop the conceptual framework of energy portfolio management (EPM) model which has been presented in the Chapter Four.

Chapter Five and Six shows the EPM simulation in the case of United States as an example of demonstrating how EPM model works in the real world. Chapter Five simulates the EPM model with only private cost in order to find out the optimal energy portfolios for energy consumption by source and sector without considering the social cost of energy resources. Chapter Six simulates the EPM model with social cost, and tries to test the sensitivity of the optimal portfolio with the increasing social costs and figure out how optimal portfolio will be impacted and changed due to the levels of social costs.

Chapter Seven concludes the dissertation with main findings.

Chapter 2 Research Objectives

The Objectives of this dissertation are to:

1. Target the needs of EPM Model by examining the current production and consumption of various energy resources, and current debates and theories regarding traditional and renewable energy;
2. Develop a conceptual framework for EPM Model to provide a step-by-step guidance for energy consumer about how to optimize the energy consumption with lower portfolio cost and associated risk;
3. Simulate the EPM model in the case of United States using Optimization Techniques from two dimensions: with only private cost and with social cost and see how EPM model works in the real world;
4. Test the sensitivity of optimal portfolio (from EPM model simulation) to the increase of social costs, and figure out how optimal portfolio will be impacted and changes due to the involvement of social costs.
5. Provide advice or suggestions to energy consumers and policy decision makers about how to select the optimal energy and portfolio in the situation of with or without the social cost.

Chapter 3 Literature Review

3.1 Energy Resources: traditional vs. renewable

Energy, by definition, is the resources that we're using every day for lighting, heating, transportation, etc. According to U.S. Energy Information Administration, energy can be classified into renewable or nonrenewable based on their availability of supply (http://www.eia.gov). Nonrenewable energy, such as oil, natural gas, coal, and nuclear power, are the resources that come from the earth and can't be replenished in a short period of time. Oil, natural gas, coal are also called fossil fuels. Renewable energy, such as biomass, hydropower, geothermal, wind, and solar, is the new alternative resources that can be replenished. The consumption of renewable energy has increased dramatically in the recent years, and has been expected to continue to grow in the next 30 years.

Figure 3-1 shows the U.S. historical energy consumption by source from 1775 to 2009. Petroleum has remained as the first major source for years, and the consumption of petroleum has been increased largely since early 1910. Natural gas and coal are the second largest energy resource, play very important role in the energy consumption. Nuclear power became a new source for energy consumption since 1970 (Figure 3-2). Wood, one of the renewable energy, has been used as early as 1775, even earlier than the usage of coal and petroleum. Another renewable energy, hydroelectric, has also a long history in the energy consumption. However, there's only small amount of energy consumption coming from renewable energy. As the development of renewable technology, renewable energy consumption has increased from approximately 3 quadrillion Btu to 8 quadrillion Btu (Figure 3-2).

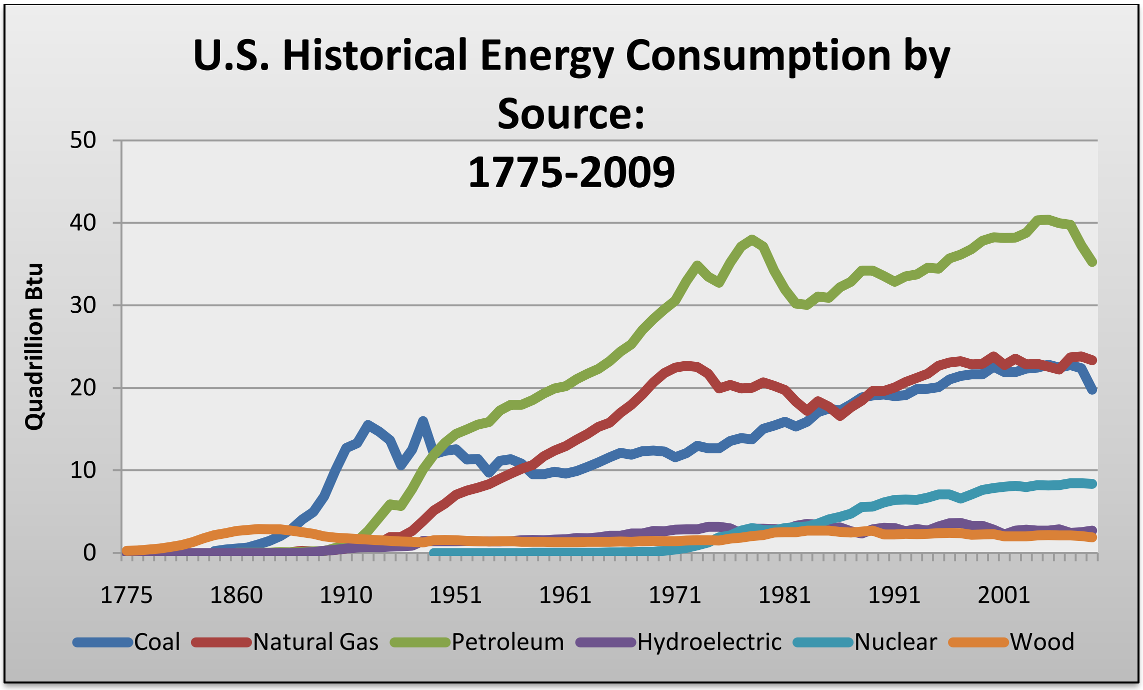

Figure 3-1: U.S. Historical Energy Consumption by Source: 1775-2009

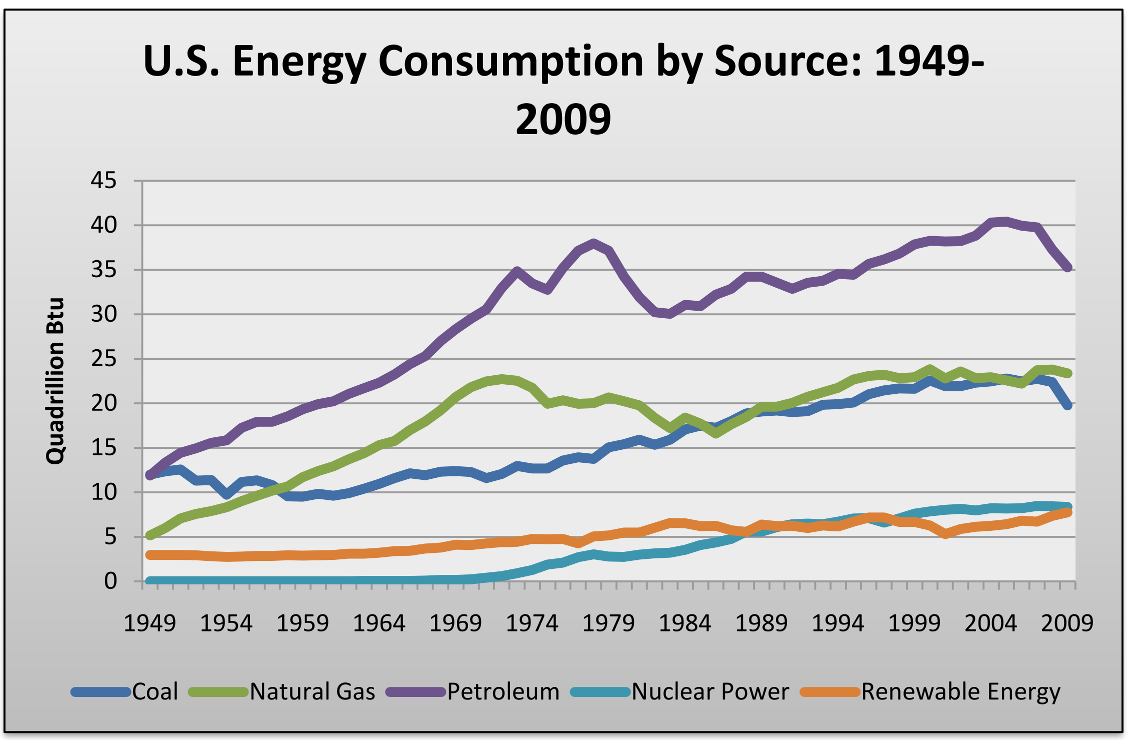

Figure 3-2: U.S. Energy Consumption by Source: 1949-2009

Figure 3-3 summarizes the percentage of energy consumption by source from 1949 to 2009. Petroleum is the largest energy consumption resource, and accounts for 41.65% on average in the overall energy consumption (see Table 3-1). The second largest energy consumption resources are coal and natural gas, coal consumption dropped a lot since 1949 while the consumption of natural gas increases, and account for on average 22.46% and 25.11% respectively. The consumption of nuclear and renewable energy is small amount in the overall consumption, only 3.78% and 7.07% on average respectively.

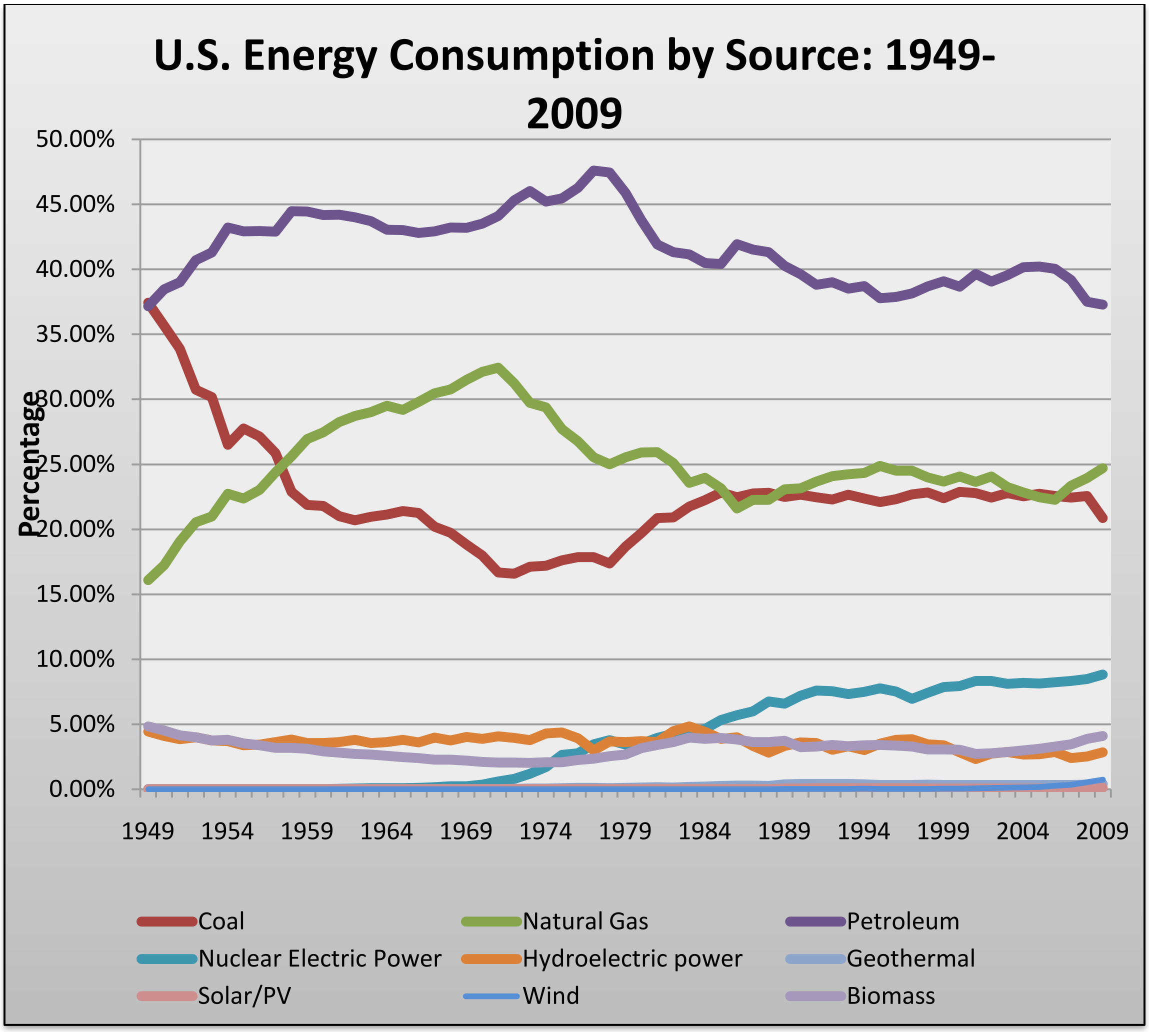

Figure 3-3: U.S. Energy Consumption (Percentage) by Source: 1949-2009[1]

Range	Coal	Natural Gas	Petroleum	Nuclear Electric Power	Hydro-electric power	Geothermal	Solar/ PV	Wind	Biomass
Min	16.58%	16.09%	37.15%	0.00%	2.33%	0.00%	0.00%	0.00%	2.02%
Max	37.44%	32.43%	47.59%	8.83%	4.83%	0.42%	0.11%	0.74%	4.84%
Mean	22.46%	25.11%	41.65%	3.78%	3.56%	0.20%	0.06%	0.11%	3.13%

Table 3-1: Energy Consumption Range by Source

[1] Source: Energy Information Administration, see Appendix 2 for data.

Another perspective of monitoring energy consumption is the energy consumption by sector: residential, commercial, industrial and transportation. The Figure 3-4 shows the energy flow from energy raw material to end consumers. The raw energy resources are collected and produced to the final energy products, and finally sell to energy consumers. Energy has been used in various purposes: transportation, electricity, heating, lighting, and manufacturing (Figure 3-5). Fossil fuels as the main traditional energy resources, such as coal, natural gas and petroleum, are mostly used for electricity, manufacturing, transportation and heating, and account for more than 80% of total consumption. Renewable energy, such as biomass, hydropower, geothermal, wind and solar, are mostly used for electricity and heating, account for less than 10 % of total consumption.

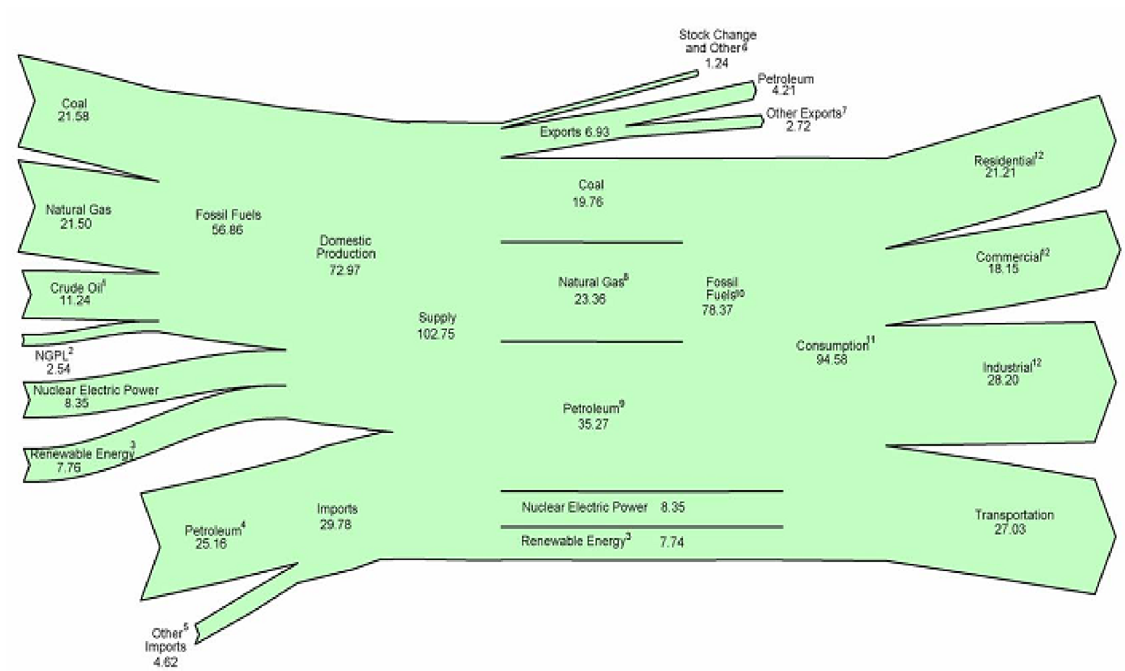

Figure 3-4: Energy flow Source[1]

[1] Source: U.S. Energy Information Administration: Annual Energy Review 2009

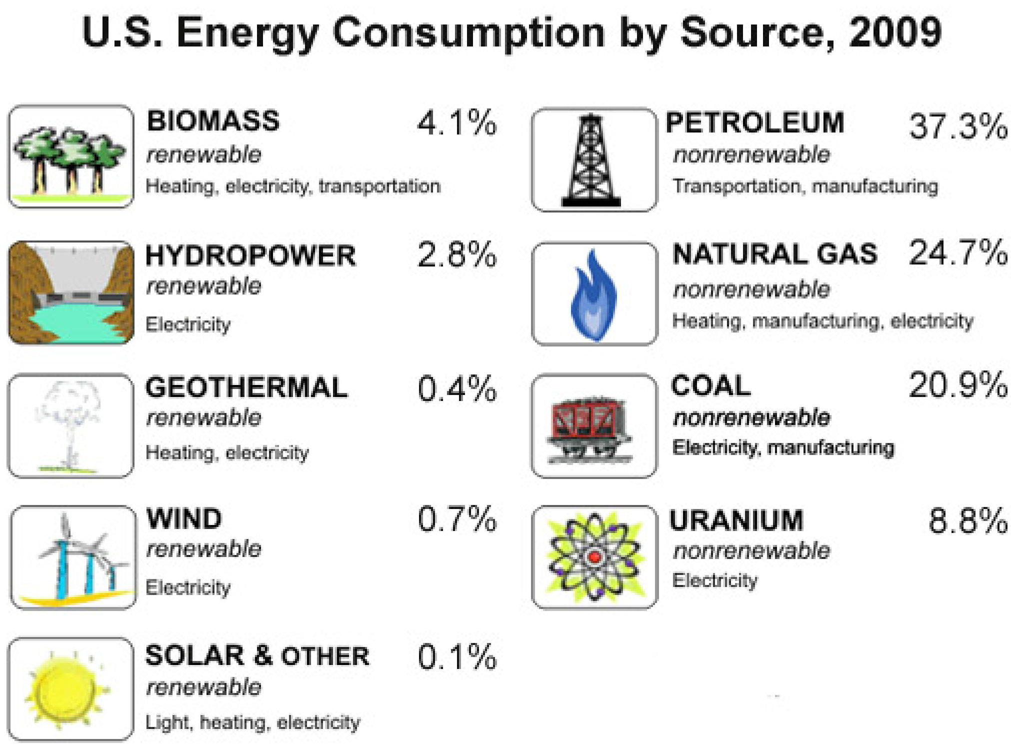

Figure 3-5: U.S. Energy Consumption by Source[1]

3.1.1 Traditional Energy

Petroleum is a broad class of liquid hydrocarbon mixtures that come from the earth, usually includes crude oil, unfinished oils, and other refined petroleum products. Through the refinery, crude oil can produce a number of petroleum products, such as gasoline, diesel, jet fuel, ethane, propane, etc. The crude oil producing countries in the world can be divided into two groups: OPEC and non-OPEC. The oil producing nations in the OPEC are Saudi Arabia, Iran, Iraq, United Arab Emirates, Kuwait and Nigeria. The main oil producing countries in the group non-OPEC are Russia, United States, Mexico, Canada, China, Persian Gulf Nations, etc. (Figure 3-6).

[1] Source: EIA Annual Energy Review 2009.

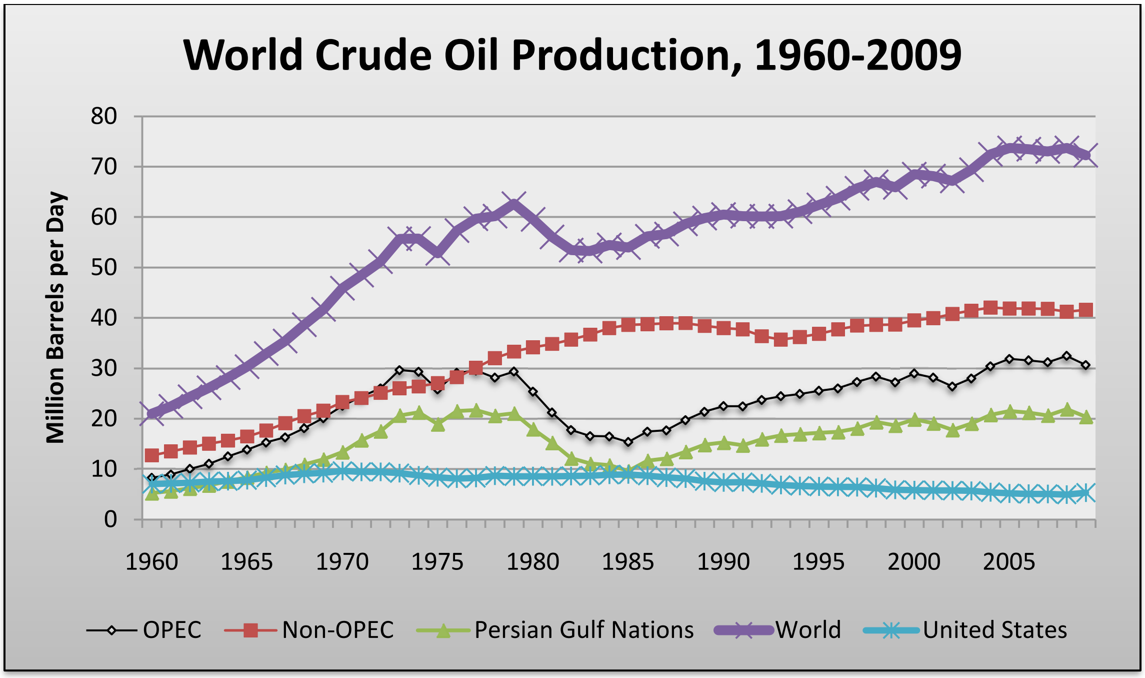

Figure 3-6: World Crude Oil Production 1960-2009

The refining products from crude oil are used widely, especially in transportation sector. A 42- US gallon barrel of crude oil can provide roughly more than 44 gallons of petroleum products which are used for different purposes (EIA, 2009). The petroleum accounts for a big part of overall energy consumption, Figure 3-7 shows the energy consumption by region, Figure 3-8 is the top 10 petroleum consuming countries. United States is the major petroleum country which consumes more than twice than other countries, and some developing countries, such as China, India, Brazil are consuming more and more petroleum. As the dramatic increase of demand, the price of crude oil in the United States rises rapidly, especially after 2000, and becomes very volatile (Figure 3-9).

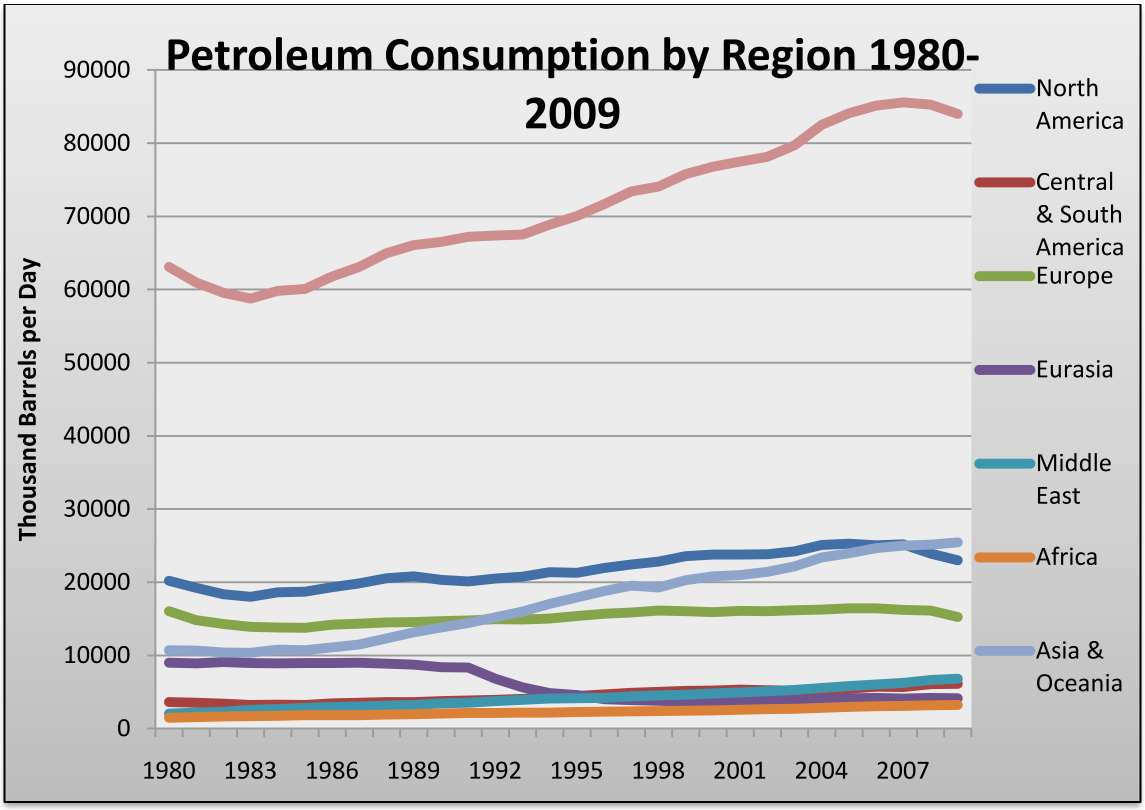

Figure 3-7: Petroleum Consumption by Region 1980-2009

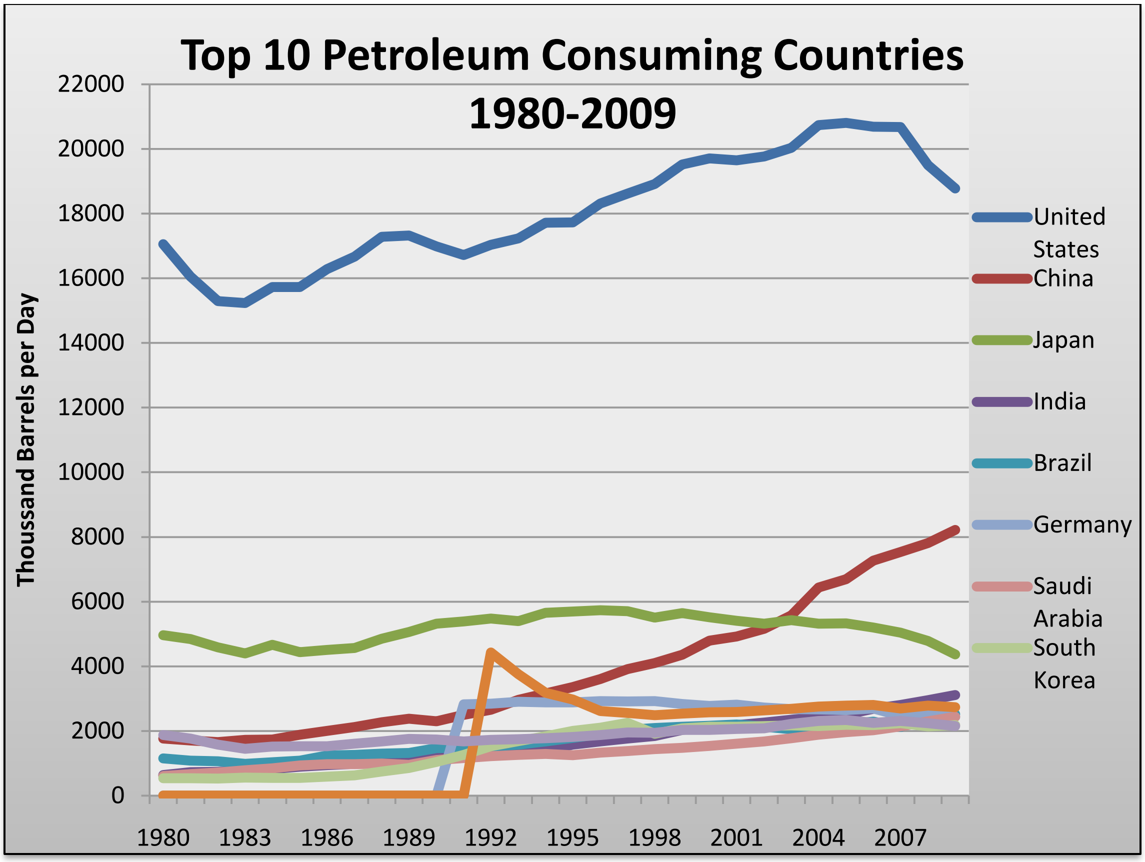

Figure 3-8: Top 10 Petroleum Consuming Countries 1980-2009

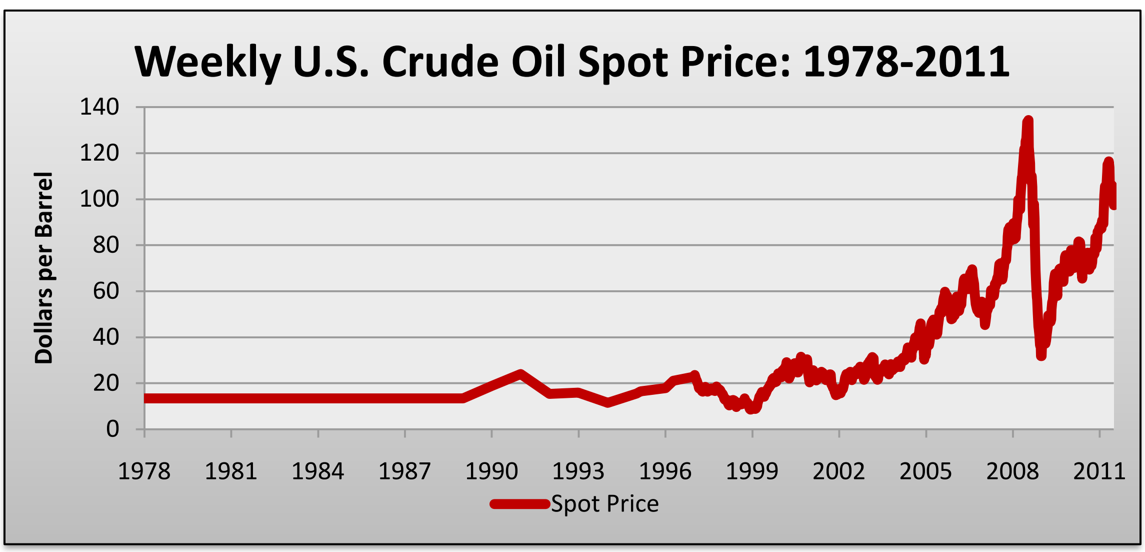

Figure 3-9: Weekly U.S. Crude Oil Spot Price: 1978-2011

Coal, as the second largest energy resource, has been used mostly for electricity and manufacturing. The production and consumption of coal in the United States have increased more than two folds from less than 500 million short tons in 1949 to more than 1000 million short tons in 2009, and the production of coal is slightly more than consumption (Figure 3-10). Figure 3-11 shows the price fluctuation of coal from 1949 to 2009, and the price of coal is around $30 per short ton.

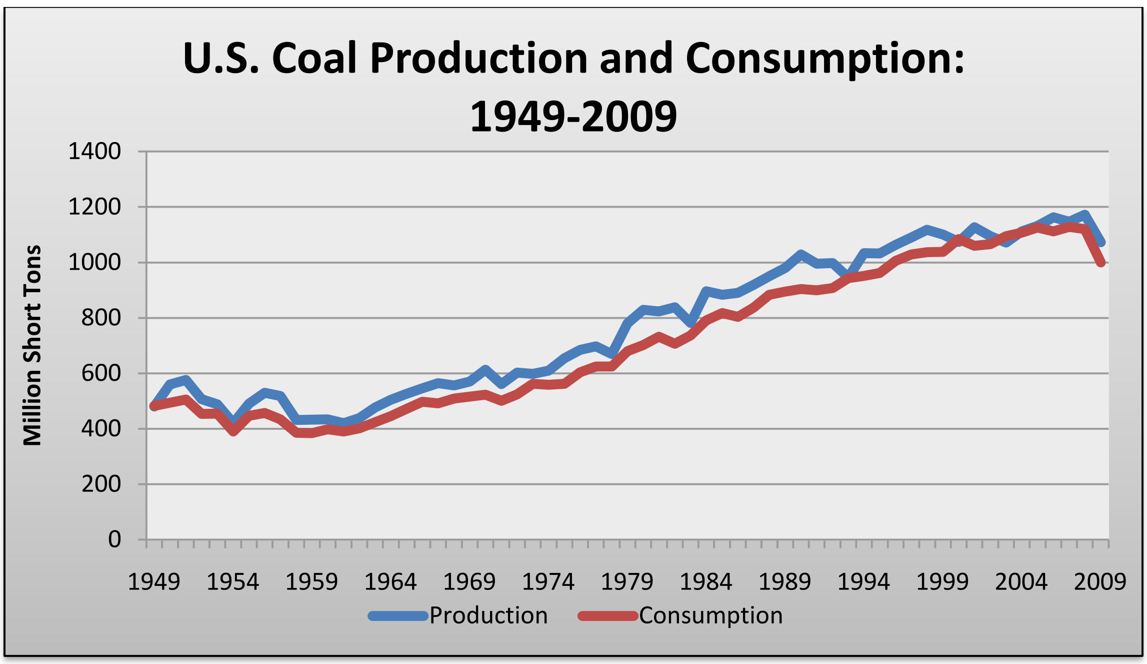

Figure 3-10: U.S. Coal Production and Consumption: 1949-2009

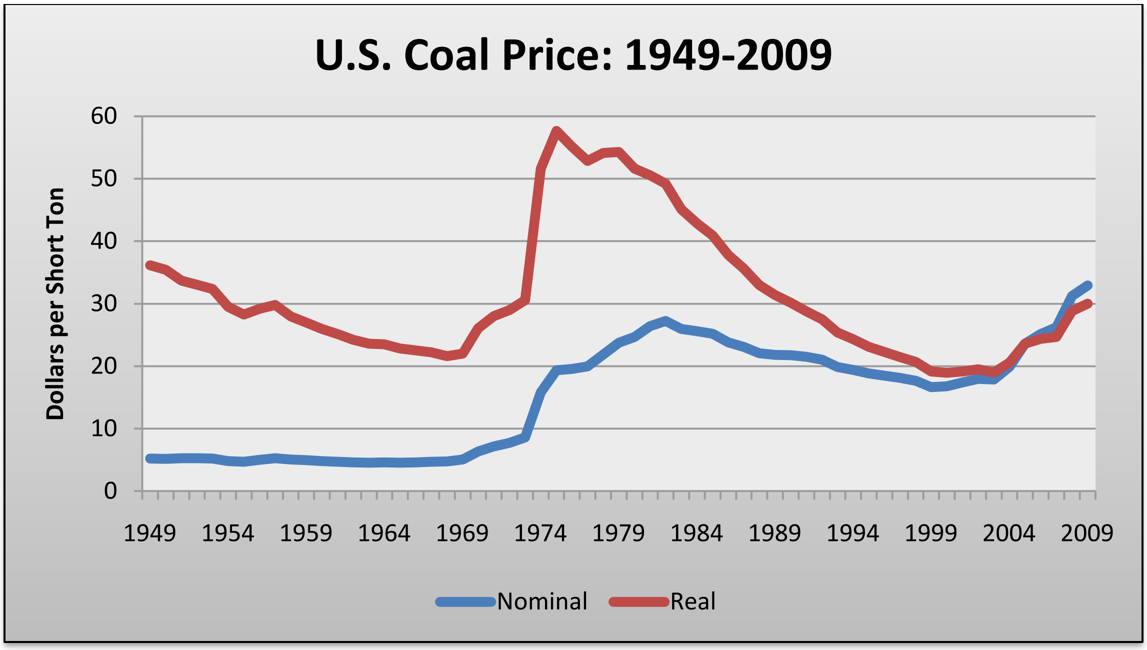

Figure 3-11: U.S. Coal Price: 1949-2009

Natural gas, one of the nonrenewable energy, has been used for heating, electricity and manufacturing. In the United States, the production of natural gas was only around 5100 billion cubic feet in 1949, and in 2009 it has reached more than 22000 billion cubic feet. The consumption kept close to the production till the year of 1967, the consumption of natural gas exceeded the production (Figure 3-12). In 2000, the consumption of natural gas is 4,151 billion cubic feet more than production, and the price of natural gas becomes more expensive and volatile (Figure 3-13). Prices for consumers are different by sectors, and residents pay higher price for natural gas compared to business and industries (Figure 3-13).

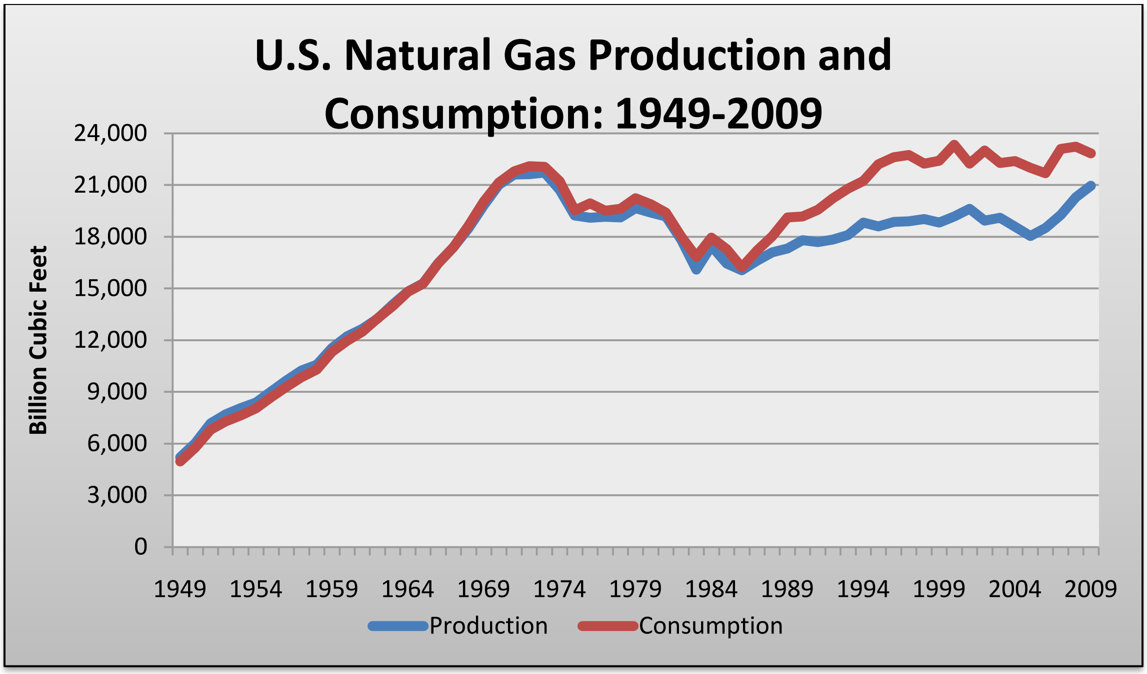

Figure 3-12: U.S. Natural Gas Production and Consumption: 1949-2009 (EIA AER 2009)

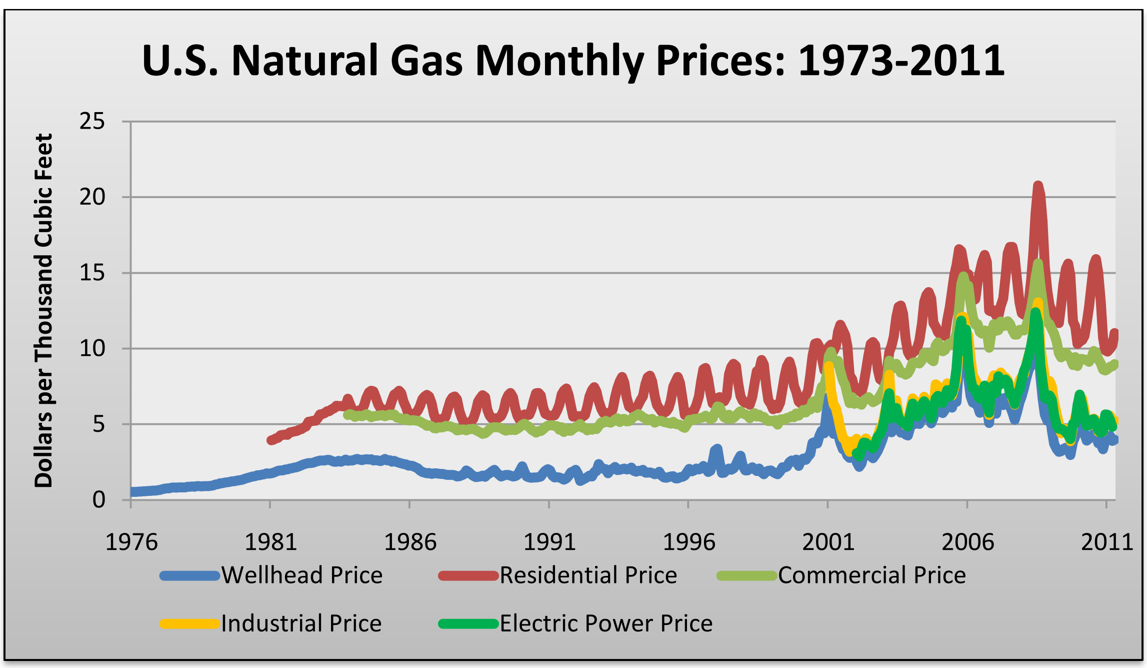

Figure 3-13: U.S. Natural Gas Monthly Prices: 1973-2011[1]

[1] Source: EIA natural gas price: 1973-2011.

Besides the concerns about the limit and availability of traditional energy resources, there is another rising concern on the climatic threat of additional carbon and the emission of CO_2 which had huge influence on the global climate change. Overall, regarding to the traditional energy, especially petroleum, major concerns are: 1) the rapid oil demand driven by the development of emerging economies, the increase of world population, and the development of the whole society with higher standard of living; 2) the limited availability of nonrenewable natural resources; 3) the rising development cost, such as the exploration and development cost of new oil fields; 4) the impact on the global climate environment. Therefore, after all of these concerns and discussions, the renewable resources become into the picture, such as wind power, solar energy, biomass and PV etc.

3.1.2 Renewable Energy

Renewable energy, as newly developed resources, has many advantages compared to traditional energy. For example, renewable energy has no impact on the climate environment, has been called green or clean energy, and most of them come from the natural and permanent resources, such as wind, sun and the land. The five most used renewable sources are biomass (including wood and wood waste, municipal solid waste, landfill gas, and biogas, ethanol, and biodiesel, EIA), water (hydropower), geothermal, wind, and solar.

In the United States, renewable energy has a very long history, for example, as early as 1775 United States has already started to use wood as the energy resource, and hydroelectric power around 1900s (Figure 3-1). Today renewable resources widely used in the United States are biomass (including wood, waste, and biofuels), hydroelectric power, geothermal, solar/PV, and wind. Biomass is used mostly for heating, electricity and transportation, hydroelectric power and wind are used for electricity, geothermal is for heating and electricity, and solar/PV is consumed for lighting, heating and electricity (Figure 3-5).

In 2009, United Stated has produced 7,761 trillion Btu from renewable energy, consumed about 7,744 trillion Btu, and the production and consumption of renewable energy almost equal (Figure 3-14). The overall consumption from renewable energy accounts for around 8.2% of total energy consumption in the United States (Figure 3-15), just a small portion in the total energy consumption; however, it tends to rise in the future due to the pressure from crude oil and the requirement from government.

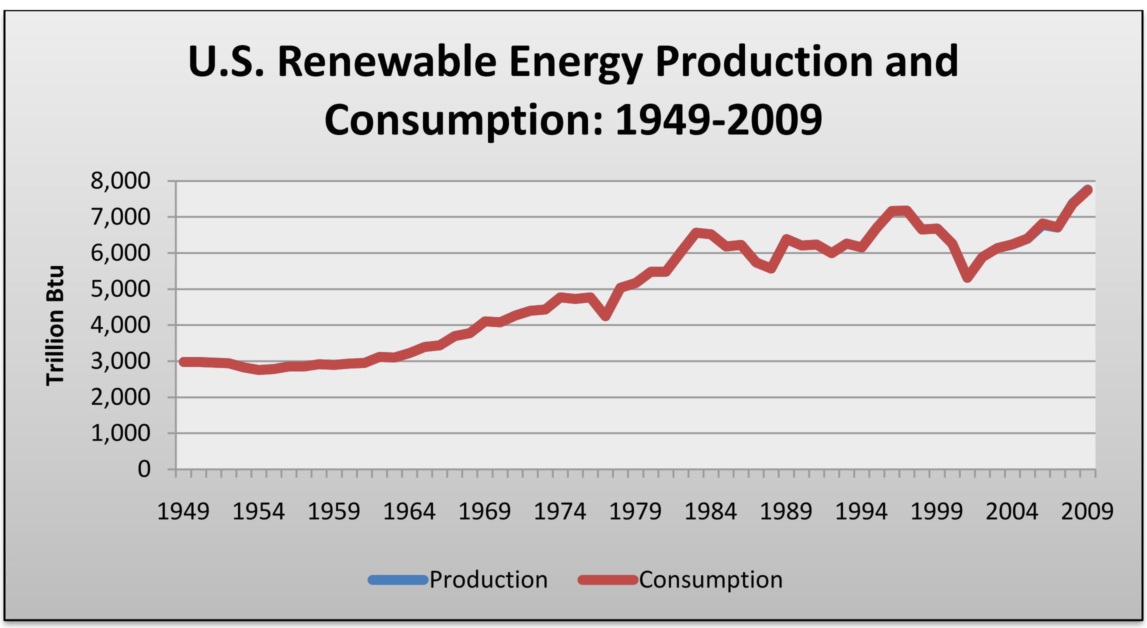

Figure 3-14: U.S. Renewable Energy Production and Consumption: 1949-2009

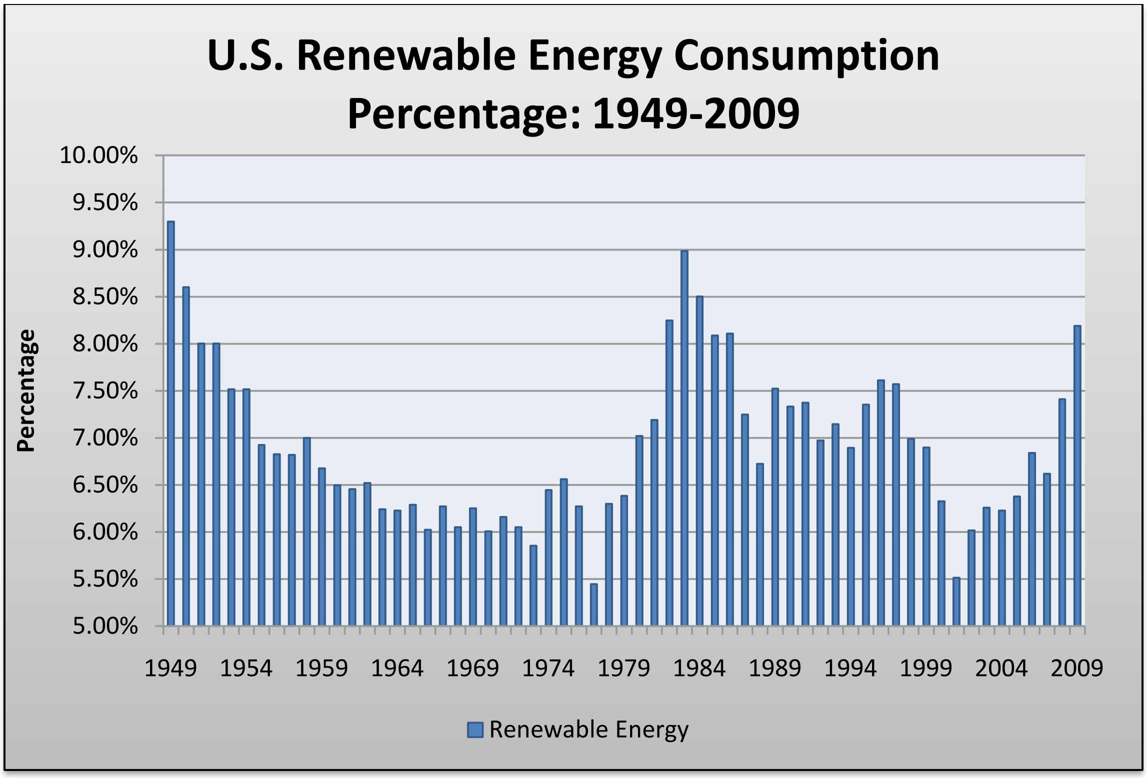

Figure 3-15: U.S. Renewable Energy Consumption (Percentage): 1949-2009

Renewable fuels, such as ethanol, are also used for transportation and to provide heat for homes and businesses. Unlike fossil fuels, non-biomass renewable sources of energy (hydropower, geothermal, wind, and solar) do not have direct greenhouse emission. Emerging renewable technologies and resources are those that are not considered conventional, for example, Digester Gas, Ocean Wave, Ocean Thermal, Tidal Current, and Fuel Cells. The availability of renewable energy is mainly associated with its physical geography; Table 3-2 below shows the availability of energy resources in some states of United States.

Sates	Solar	Wind	Biomass	LF	Biogasc	MS	Geoth	All Hydro	Increm. Hydro	Small Hydro	Fuel Cells	RE-only Fuel	Ocean/ Wave/ Tidal

				G		W						Cells	
AZ	x	x	x	x	x		x		x	x		x	
CA	x	x	x	x	x	x	x			x			x
CO	x	x	x	x	x		x			x	x	x	
CT	x	x	x	x						x			x
DE	x	x	x	x	x	x	x			x		x	x
DC	x	x	x	x	x	x	x	x				x	x
HI	x	x	x	x	x	x	x	x				x	x
IL	x	x	x	x		x			x				
IA	x	x	x	x	x					x	x		
ME	x	x	x	x		x	x	x					x
MD	x	x	x	x	x	x	x	x				x	x
MA	x	x	x	x	x	x		x				x	x
MN	x	x	x	x	x	x				x		x	
MT	x	x	x	x	x	x	x			x		x	
NV	x	x	x	x	x		x			x			
NH	x	x	x	x	x	x	x			x	x		x
NJ	x	x	x	x			x			x			x
NM	x	x	x	x	x	x	x		x		x	x	
NY	x	x	x	x	x			x	x	x			x
NC	x	x	x	x	x		x			x			x
OR	x	x	x	x	x		x	x			x	x	x
PA	x	x	x	x	x		x	x		x			
R.I.	x	x	x	x	x	x	x			x		x	x
TX	x	x	x	x			x	x					x
WA	x	x	x	x	x		x		x				x
WI	x	x	x	x			x			x		x	x

Table 3-2: United States State RPS Resource Availability[1]

Although renewable energy has many advantages, such as no other energy required for production and no carbon dioxide emission for the environment; they still have some

[1] Source: Database of State Incentives for Renewable Energy (DSIRE), x represents available.

disadvantages. For example, the exploration and development costs are still high (the prices of renewable energy are still relatively higher than some traditional energy) and also the limitation of implementation. The important concern about renewable technologies is how to use renewable energy more efficient and cost-effective. One measure of the energy effectiveness of a renewable technology is the energy payback period, the length of time required to repay the energy used in the construction after the system begins operation, another measure is the energy return on energy investment ratio (Kreith & Goswami, 2007). As the development and maturity of renewable energy technologies, renewable energy becomes more and more attractive, and more and more countries are willing to put more efforts on renewable energy.

3.1.3 Energy Measurement

Due to the variety of energy resources, the measurements are different from each other. Some popular physical units are:

- Barrels or gallons for petroleum
- Cubic feet for natural gas
- Tons for coal
- Kilowatt hours for electricity

In order to compare the cost of different energy resources, a common unit for measure is needed. There are some options: British Thermal Units (Btu), barrels of oil equivalent, metric tons of oil equivalent, metric tons of coal equivalent, and terajoules. In the United States, the most common used unit for energy comparing is Btu, a measure of heat energy.

According to U.S. Energy Information Administration (EIA), Btu Content of Common Energy Units are:

- 1 barrel (42 gallons) of crude oil = 5,800,000 Btu
- 1 gallon of gasoline = 124,238 Btu (based on U.S. consumption, 2008)
- 1 gallon of diesel fuel = 138,690 Btu
- 1 gallon of heating oil = 138,690 Btu
- 1 barrel of residual fuel oil = 6,287,000 Btu
- 1 cubic foot of natural gas = 1,027 Btu (based on U.S. consumption, 2008)
- 1 gallon of propane = 91,033 Btu
- 1 short ton of coal = 19,977,000 Btu (based on U.S. consumption, 2008)
- 1 kilowatt hour of electricity = 3,412 Btu

3.2 Peak Oil Theory

Peak oil theory can be explained as a kind of development theory, rather than a crisis theory (Zhao, Feng& Hall, 2009), which improves people's recognition of peak oil, promotes more efficient energy consumption, and encourages the energy mitigation. Geologists believes that crude oil is a finite resources, and the crude oil production will reach the maximum ("peak") at some point in the future (Hirsch, Bezdek & Wendling, 2005). Oil peaking doesn't mean we're running out of oil, however, the oil production will still continue after the peak, but at a low production rate. In other words, we're running out of cheap oil. The peak oil theory has first been presented by American geoscientist Marion King Hubbert in 1956. He pointed out that oil production tends to follow a bell-shaped curve, also called "Hubbert's peak" or "Hubbert's curve", and predicted it would reach a peak in 1970 in the United States which has eventually proved correct, and a global peak in 2000 (Hornby, 2009).

3.2.1 Peak Oil Debates

Regarding the peak oil theory, there are two different types of discussions: “Peakists” argue that oil production is determined by geology and will reach the maximum (“peak”) within a few years or decades; while “optimists” argue that the economic factors overtake the geologic arguments, and come to the conclusion that the peak oil won’t occur for many decades in the future (Fisher, 2008). Hubbert (1956) has presented a mathematical model using logistic equation, and predicted the peaking of oil production based on the assumption that the ultimate recoverable amount of oil (URR) is limited. The supports of peakists are M. King Hubbert (1956, 1982), K. Deffeyes (2001, 2002, 2003), C. Campbell (2003) and J. Leherrere (1998, 2003).

However, the opposite supporters argue there won’t be oil peaking for many decades due to some limitations in the Hubbert peak theory, such as missing economic factors in the logistic equation of the Hubbert peak theory, and the inappropriate assumption of the fixed amount of available oil (Fisher, 2008). The criticisms are coming from Michael Lynch (2003, 2004), the IEA (2000) and some energy financial analysts.

3.2.2 Peak Oil Issues

Basically, the debates on peak oil theory from both sides are surrounding on two issues: the timing of peak oil and the consequences. Regarding the timing of peak oil, researchers have different predictions. Hubbert predicted the oil production would reach peak during 1970 and a global peak around 2000. Table 3-3 shows a summary of peak oil date with timing predictions (Almeida & Silva, 2009). The prediction results are various due to different approaches they've used. The difficulties of predictions are also coming from the geological complexities, measurement problems, pricing variations, demand elasticity and political influences (Hornby, 2008).

Date of Forecast	Source	Peak Oil Date	Reference
2000	Bartlett	2004-2014	Bartlett (2000)
2000	EIA	2021-2112	Wood and Long (2000)
2000	IEA	Beyond 2020	IEA (2000)
2001	Deffeyes	2003-2008	Deffeyes (2001)
2002	Nemesis	2004-2011	Nemesis (2002)
2002	Smith	2011-2016	Smith (2002)
2003	Simmons	2007-2009	Simmons (2003)
2003	Deffeyes	Before 2009	Deffeyes (2003)
2003	Campbell	Around 2010	Campbell (2003)
2003	World Energy Council	After 2010	WEC (2003)
2003	Laherrere	2010-2020	Laherrere (2003a,b)
2003	Shell	2025 or later	Davis (2003)
2003	Lynch	No visible peak	Lynch (2003)
2004	EIA	2021-2112	Wood et al. (2004)
2004	Bakhtiari	2006-2007	Bakhtiari (2004)
2004	Skrebowski	After 2007	Skrebowski (2004)
2004	Goodstein	Before 2010	Goodstein (2004)
2004	CERA	After 2020	Jackson & Esser (2004)
2005	Koppelaar	After 2010	Koppelaar (2005)
2006	Skrebowski	After 2010	Skrebowski (2006)
2006	Smith	2011	Smith (2006)
2006	Koppelaar	After 2012	Koppelaar (2006)
2006	IEA	After 2030	IEA (2006)

2006	CERA	2035	Jackson (2006)
2007	Robelius	2008-2018	Robelius (2007)
2007	Koppelaar	2015	Koppelaar (2007)
2007	Laherrere	About 2015	Laherrere (2007)
2008	CERA	After 2017	CERA (2008)
2008	Shell	2020 or later	Shell (2008)
2009	Maggio & Cacciola	2009-2021	Maggio & Cacciola (2009)

Table 3-3: Peak Oil Projected Dates

The consequences of oil peak are many, Hirsch et al. (2005) had pointed out in his report that the major impact of oil peak would be the higher oil prices and the increased oil price volatility. As the oil production reaches the peak, the production of oil will tend to decline at some rate, while the demand of crude oil still tends to increase dramatically, as the situation goes, the oil peaking finally will cause the supply disruption. If the supply and demand theory works without other interventions from the outside world, the price of oil should keep increasing as the supply disruption caused by oil peaking. Figure 3-16 shows the changes of spot oil price since 1978, it shows that the current oil price has increased more than four folds compared to the price in 1978, and it becomes much more volatile during recent ten years.

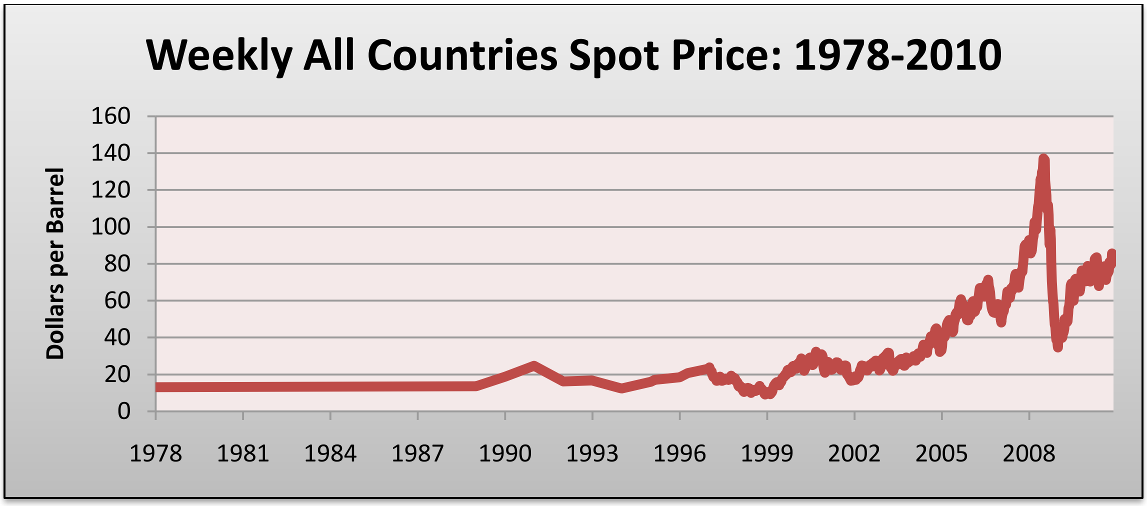

Figure 3-16: Weekly All Countries Spot Price[1]

According to most of current researches, oil peak is inevitable, but the timing is uncertain (Hirsch et al., 2005). If we'll experience the peak sooner or later, it would be better to prepare in advance. Hirsch (et al., 2005) had created a simulation with three mitigation scenarios. The results show that the mitigation effect will require substantial time: 1) if wait until world oil production peak before taking actions, it would have a significant liquid fuel deficit for more than two decades (Figure 3-17); 2) if initiate a mitigation crash program 10 years before oil peaking, it would have a liquid fuel shortfall for a decade (Figure 3-18); 3) if initiate a mitigation crash program 20 years before oil peaking, it would have the possibility of avoiding a liquid fuel shortfall (Figure 3-19). The results demonstrate that the earlier action, the less impact of peak oil.

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[1]Source: U.S. Energy Information Administration: weekly spot price

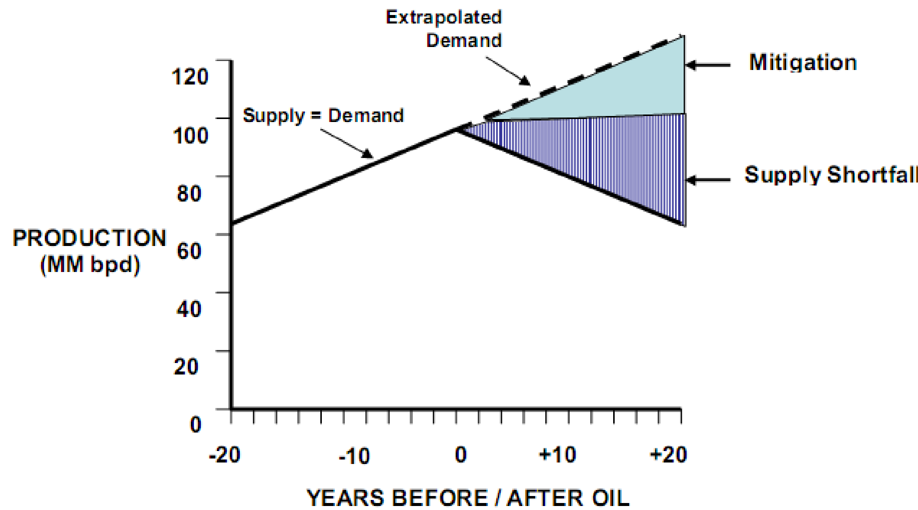

Figure 3-17: Action taken at the time of oil peaking[1]

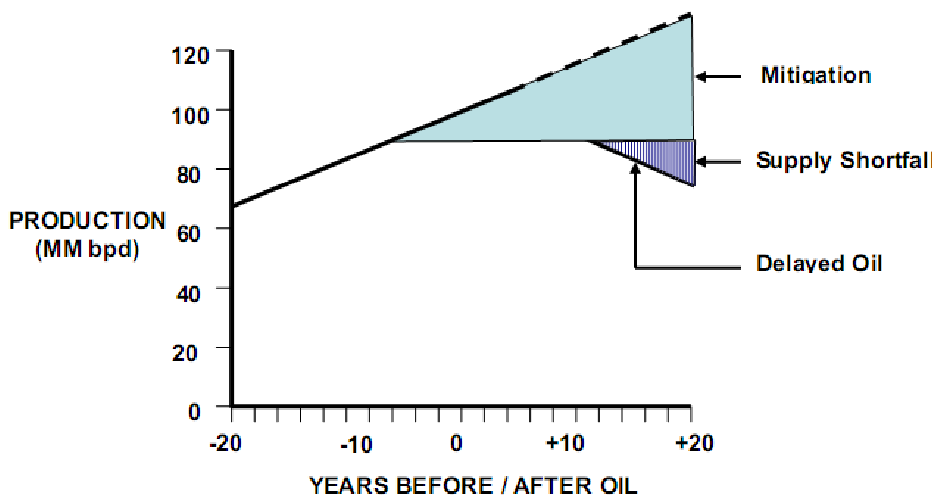

Figure 3-18: Action taken 10 years before oil peaking

[1] Source: Hirsch et al., 2005

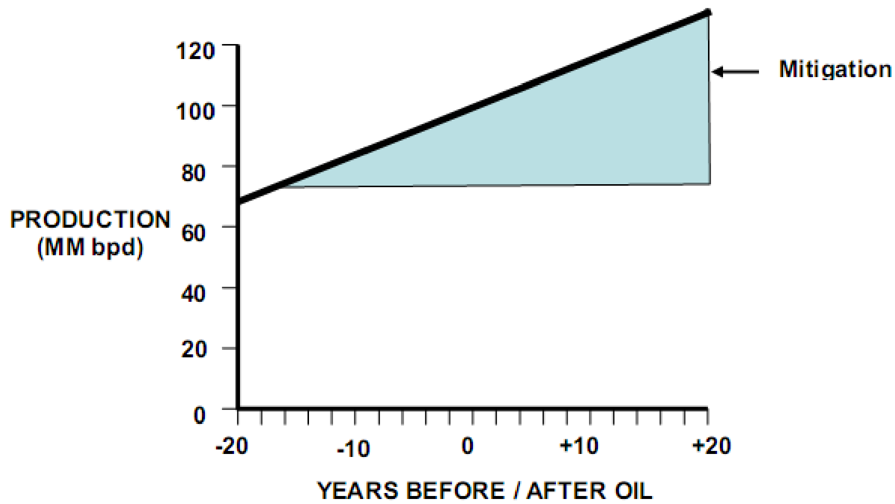

Figure 3-19: Action taken 20 years before oil peaking

3.2.3 Peak Oil Solutions

What can we do regarding oil peak? There are two possible solutions: energy mitigation and renewable energy. Energy mitigation is a general concept that describes the mitigation process from conventional energy resources to renewable energy resources. It is not an easy process (Hirsch et al., 2005), requires a long and complex period of time to accomplish. For example, replacing the current transportation tools, like the trucks, trains and airplanes which mainly relies on the conventional liquid fuels, to the new more efficient transportation tools may take more than 10 years. Energy mitigation also largely relies on the development of renewable energy which is considered to be more efficient and less impact on environment.

These peak oil discussions has shown that renewable energy has already become an inevitable and necessary alternative energy, therefore, the renewable energy has been chosen as the comparable resources in the EPM model. As the dramatic increase of oil demand, the increasing oil price and price volatility due to oil peaking, the rise of renewable energy, and the concerns from the environment and society, the overall energy consumption structure will finally be changed or switched in the near future. Therefore, this dissertation takes both traditional and renewable energy resources into the EPM model, and tries to find out the better combination for energy consumption.

3.3 Renewable Portfolio Standard

A Renewable Portfolio Standard (RPS) is a policy that requires the minimum percentage or quantity of their electricity supplies that retailers must provide from renewable energy resources (Cory & Swezey, 2007; Morris, 2009). As far as May 2011, United Stated has 36 states and the District of Columbia enacted RPS policies, ranging from 10% to 40% in Hawaii (Table 3-4). And this table illustrates the importance of renewable energy on the energy consumption, especially for the electricity.

State	RPS Policies
AZ	15% by 2025
CA	33% by 2020
CO	30% by 2020
CT	23% by 2020
DC	20% by 2020
DE	25% by 2026
HI	40% by 2030
IA	105 MW
IL	25% by 2025
KS	20% by 2020
MA	22.1%by 2020
MD	20% by 2022
ME	30% by 2000
MI	10%&1,100MW by 2015
MN	25% by 2025
MO	15% by 2021
MT	15% by 2015
NC	12.5% by 2021
ND*	10% by 2015 (goal)
NH	23.8% by 2025
NJ	20.38%RE by 2021

NM	20% by 2020
NV	25% by 2025
NY	29% by 2015
OH	25% by 2025
OK*	15% by 2015 (goal)
OR	25% by 2025
PA	18% by 2021
RI	16% by 2020
SD*	10% by 2015(goal)
TX	5,880 MW by 2015
UT*	20% by 2025(goal)
VA*	15% by 2025(goal)
VT*	20% by 2017(goal)
WA	15% by 2020
WI	10% by 2015
WV*	25% by 2025 (goal)

Table 3-4: U.S. Renewable Portfolio Standard by State[1]

However, Sovacool (2008) argued that the portfolio approach with the renewable energy in the current energy environment is still favoring the fossil fuel and nuclear technologies and ignoring the different full social costs of energy systems (Sovacool, 2008), and the portfolio taking full social cost into consideration would make sense. Renewable energy, as the main cheap resources for electricity generation, is much clean energy with very little or no environmental impacts, and should be included and have a comparable amount with traditional energy in the energy portfolio.

Therefore, an optimal energy portfolio approach should give renewable energy the same opportunity as traditional energy resources, and the EPM in this dissertation will optimize the energy consumption from all the available energy resources including renewable energy. Energy portfolio management in the dissertation has been defined as the consumption management of energy resources from two dimensions of optimization:

[1] Source: Database of State Incentives for Renewable Energy (DSIRE) www.dsireusa.org/May 2011, * States with RPS goals not mandatory requirements.

minimizing the energy portfolio cost and lowering the associated portfolio risk. Literatures about the mean-variance portfolio theory and its applications are examined in this chapter.

3.4 Energy Portfolio Theory

3.4.1 Mean-Variance Portfolio (MVP) Theory

Modern Portfolio theory (also called portfolio theory), developed in the 1950s through the early 1970s, was considered as a very important improvement in the field of financial economics. Harry Markowitz, who first presented the portfolio theory in his paper "Portfolio Selection" (1952), had won the Nobel Prize in the year of 1990 for his contribution to portfolio theory. In his researches (1952, 1959), he has developed a mean-variance method for selecting the optimal portfolio which provides the solution to the portfolio optimization problem. Several other researchers have extended Markowitz's research, for example, James Tobin (1958) expanded Markowitz's portfolio theory by adding a risk-free asset, Mitchell and Braun (2002) analyzed the portfolio theory with the transaction cost included, and Luenberger (1998) discussed the portfolio theory using the multiple periods.

From the investors' perspective, Markowitz assumes that there's a portfolio that gives both maximum expected return and minimum variance (Markowitz, 1952). To measure the return and risk, the mean variance methods use the expected return of an asset, the variance of the asset to measure the risk of that asset. The return of portfolio is the weighted sum of assets i:

$$E(R_p) = \sum_i W_i E(R_i) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The variance σ^2 of the portfolio return is

$$\sigma^2 = \sum_i W_i^2 \sigma_i^2 + \sum_i \sum_{j \neq i} W_i W_j \sigma_i \sigma_j \rho_{i,j} \ \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where:

$E(R_p)$: the expected return of the portfolio;

$E(R_i)$: the expected return on the asset i;

W_i: the weight or percentage or share of investment on the asset i, $\sum_i W_i = 1$ and $Wi \geq 0$;

σ_i: the standard deviation of asset i;

$\rho_{i,j}$: the covariance (correlation coefficient) between asset i and j;

Markowitz's portfolio theory assumes that the market is perfect and investors are rational, and portfolio theory is to seek an optional solution to maximize the overall return with minimal risk, therefore, the portfolio theory can be interpreted into two ways: maximize the expected return with given level of variance, or minimize the risk with given level of return (Amu & Millegard, 2009), expressed as:

Maximize $\sum_i W_i E(R_i)$, with the conditions of $\sum_i W_i^2 \sigma_i^2 + \sum_i \sum_{j \neq i} W_i W_j \sigma_i \sigma_j \rho_{i,j} = \sigma^2$ and $\sum_i W_i = 1$;

$$\text{Minimize} \sum_i W_i^2 \sigma_i^2 + \sum_i \sum_{j \neq i} W_i W_j \sigma_i \sigma_j \rho_{i,j}, \text{ with the conditions of } \sum_i W_i E(R_i) = E(R) \text{ and } \sum_i W_i = 1;$$

Using the observed mean of return (R_i) and variance σ^2 for some period of the past, a set of efficient portfolio solutions can be found from the return-variance mix, and all the optimal points will be lined up to a line called efficient frontier in the graph of return and variance. Efficient frontier provides the optimal combination of return and variance. Basically, the portfolio theory is trying to find out the optimal percentage (W_i) that's invested in asset i, and the optimization can be achieved using Lagrange multipliers (Amu & Millegard, 2009).

3.4.2 Energy MVP

The definition of PM, drawn from a 2006 report on clean energy policies and best practices prepared by the United States Environmental Protection Agency (EPA) (Steinhurst et al., 2006):

> Portfolio management refers to energy resource planning that incorporates a variety of energy resources, including supply-side (e.g., traditional and renewable energy sources) and demand-side (e.g., energy efficiency) options. The term "portfolio management" has emerged in recent years to describe resource planning and procurement in states that have restructured their electric industry. However, the approach can also include the more traditional integrated resource planning (IRP) approaches applied to regulated, vertically integrated utilities.

MVP has been applied to capital budgeting and project valuation (Seitz & Ellison, 1995), valuing offshore oil leases (Helfat, 1988), quantifying climate change mitigation risks (Springer and Laurikka, 2002), and electricity generating planning (Awerbuch, 2003, 2004, 2005; Lesser et al., 2007; Rodoulis, 2010; Roques et al., 2006, 2009). Appendix 1 shows a summary of energy MVP applications, it shows that MVP used as a way of energy portfolio measurement is highly suited to the problem of energy planning.

Portfolio theory was initially conceived in the context of financial portfolios, where it relates expected portfolio return to expected portfolio risk, defined as the year-to-year variation of portfolio returns. Portfolio theory for energy usually uses the generating cost and risk as their proxy of return and risk. Generating cost (cent/kWh) is the inverse of a return (kWh/cent), that is, a return in terms of physical output per unit of monetary input (Lesser et al., 2007).

Expected portfolio cost $E(C_p)$, is the weighted average of the individual expected generating costs.

For the two technologies: $E(C_p) = W_1 E(C_1) + W_2 E(C_2)$

For n technologies: $E(C_p) = \sum_i W_i E(C_i)$

Where: W_i are the percentage of the technology i in the mix, and $E(C_p)$ is their expected generating costs per kWh.

To calculate the portfolio costs, cost factors are needed to be identified. The factors that have been mostly used are capital cost, fixed and variable Operating &Maintenance cost, and fuel cost (Awerbuch et al., 2004, 2005, 2005; DeLaquil et al., 2005; Roques et al., 2006; Lesser et al., 2007; Rodoulis, 2010). As the rising concern about climate change, some research has added carbon cost (especially the cost for CO_2) into their consideration (Roques et al., 2006; Lesser et al., 2007; Rodoulis, 2010). In this thesis, the cost factors are categorized into private cost and social cost. The private cost includes the capital cost for initial investment, the fixed and variable operating and maintenance cost, and fuel cost. The social cost will use CO_2 cost as a way of measuring the cost for the impact on the environment.

Expected portfolio risk, E (σ_p), is the expected year-to-year variation in generating cost. It is also a weighted average of the individual technology cost variances, as tempered by their co-variances:

For the two technologies: $E(\sigma_p) = \sqrt{{W_1}^2{\sigma_1}^2 + {W_2}^2{\sigma_2}^2 + 2W_1W_2\rho_{12}\sigma_1\sigma_2}$

For n technologies: $E(\sigma_p) = \sqrt{\sum_i W_i^2\sigma_i^2 + \sum_i \sum_{j\neq i} W_iW_j\sigma_i\sigma_j\rho_{i,j}}$

Where:

W_1 and W_2 are the percentage of the two technologies in the mix;

σ_1 and σ_2 are the standard deviations of the holding period returns of the annual costs of technologies 1 and 2 as further discussed below;

ρ_{12} is their correlation coefficient of technology 1 and 2;

$$\rho_{12} = \frac{cov(r_1, r_2)}{\sigma_1{}^2\sigma_2{}^2} \quad cov(r_1, r_2) = E\{(C_1 - E(C_1)) * (C_2 - E(C_2))\}$$

For most of energy MVP applications, the standard deviation has been used to measure the risk. Besides the standard deviation, there are also some other alternative measurements (Table 3-5). Comparing the different ways of risk measurement, standard deviation is more appropriate to measure the risk of energy technology considering the complexity of energy costs.

Possible Measures of Risk	
Risk Measure	**Description of Measurement**
Coefficient of Variation (CV): distribution's standard deviation/ its mean	Measure risk relative to return or variation in price relative to mean price
Beta: covariance/variance	Measure of systematic risk of single asset or portfolio (volatility)
Value-at-Risk (VaR)	Measure the downside risk of a portfolio, and can be applied to measure the cost increase that has a certain probability
Component value at risk	Measures the marginal contribution to value at risk of each element within the overall portfolio
Credit value at risk	Measures potential credit exposure on individual transactions as well as the total credit value at risk for the portfolio
Enterprise-wide risk measures	Aggregates market, operational, credit, and regulatory risk
Costs at risk	Measures probability that a portfolio's costs will go up or down.
Rates at risk	Measures potential change in end customer's rates as a result of generation supply portfolio

Table 3-5: Possible Measures of Risk

3.5 Efficient Frontier Optimization

Efficient frontier for energy optimization is an optimal or efficient mix line which represents the minimum portfolio cost at any given level of portfolio risk (DeLaquil et al., 2005), or the associated least-risk portfolio at any given level of cost (Lesser et al., 2007). Efficient frontier analysis has been widely used for optimizing the electricity generating planning (Awerbuch et al., 2004, 2005, 2005; DeLaquil et al., 2005; Roques et al., 2006; Lesser et al., 2007; Rodoulis, 2010). It provides the optimal energy cost and risk combination which can be used as an indicator to compare with different energy portfolio at different risk levels so that energy consumers can minimize cost with less risk.

Efficient Frontier analysis is available from some software: Crystal Ball with OptQuest from Oracle, or @RISK with Risk Optimizer from Palisade. OptQuest, an add-in optimization tool running with Crystal Ball, can automatically search for and find the optimal solutions that meet with the defined objectives. The EPM model will use the Efficient Frontier from Crystal Ball as the optimization technique to simulate the optimal energy cost-risk mix which provides the minimal risk at some certain level of cost or the lowest cost at some certain level of risk.

In order to run Efficient Frontier analysis in the OptQuest, the objectives, distribution assumption, decision variables and bounds, and efficient frontier requirements are required before simulation. For the EPM model, the objective is to minimize the mean of portfolio cost with the requirement of standard deviation of portfolio cost must be between 0.5 and 1.5 (Figure 3-20). Distribution assumption is the probability distribution of sampling for energy cost, will be defined based on the specific energy resources and cost historical data. Decision variables are the percentages of the energy resources with a total 100% for the entire portfolio, the lower and upper bounds of decision variables define the minimal and maximal percentage allowed in the portfolio, will be set according to historical percentages of energy consumption for each energy resource. Considering the objective of EPM model, the efficient frontier should simulate and analyze the portfolio which has lower cost and less risk, therefore, the requirement of efficient frontier in this case it to vary the lower bound of standard deviation (the measure of risk) of portfolio from 0.5 to 0.9 in steps of 0.01 (Figure 3-20). With these settings, OptQuest will run the simulation based on the input parameter and layout the Efficient Frontier analysis results.

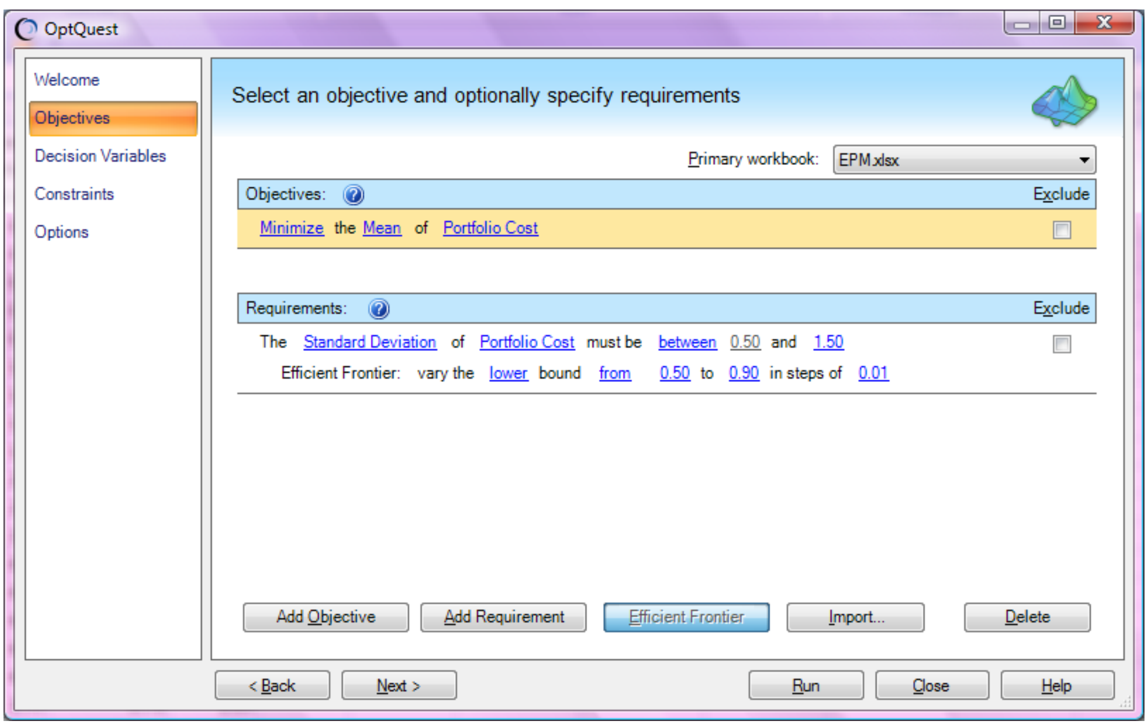

Figure 3-20: EPM Simulation Objectives

Chapter 4 EPM Model Framework

4.1 Overview

EPM model is designed to manage energy consumption, identify the optimal cost-risk combination at different level of cost or risk, and provide some possible solutions to improve the current status close to the optimal point by changing the combination of energy resources. To construct the EPM model, there are several elements needed to be examined, the available energy resources and the cost for each energy technology.

Available energy resources on the planet have been categorized into two groups in the research: traditional and renewable energy. Traditional energy sources, such as petroleum, natural gas and coal, have been used widely; however, they also come with questions. The first question is coming from peak oil theory, researchers (especially "peakists") argue that there is or will be an oil peak due to its geological limitation, and they also point out different predictions for oil peaking timing (Table 3-3). The second is the impact of emissions produced from burning petroleum products on the environment, such as climate change and global warming. As the increasing of oil price, it also causes some related problems, like the increasing costs of the petroleum related products, oil supply and demand imbalance, speculation, and so on.

On the other side, renewable energy sources come into the picture, and become a good alternative choice for energy consumption. In recent years, the technologies for renewable energy exploration and development have improved greatly, and renewable energy becomes cost comparable with traditional energy. Moreover, renewable energy considered as sustainable energy has no impact on the environment (also called "green" energy). To expand the use of renewable energy sources, some countries have enacted laws and regulations that enforce renewable energy to be used at certain percentage of the total energy consumption. For example, some states in the United States have already published the Renewable Portfolio Standards (RPS) which regulates the minimal usage of renewable energy. However, Sovacool (2008) argues that the current RPS is biased because it's still in favor of traditional energy sources, and the current energy renewable portfolio is not the best due to its disadvantages.

Considering the questions and situations from traditional and renewable energy, whether the energy consumption is efficient and how to reach the optimal or efficient consumption becomes an important question. From energy consumers' perspectives, no matter its individual resident, or commercial user, or country as a big giant energy consumer, a balanced energy portfolio solution is needed, and that's why EPM has been created and simulated.

4.2 EPM Methodology

EPM model is developed for providing an optimal energy consumption solution based on the available energy resources and energy cost structure. The purpose of the model is to find out an optimal consumption combination from traditional and renewable energy which provides the optimal combination of energy cost and risk. The model is created based on two components: energy resources (traditional and renewable) and energy cost structure including the private production cost and social cost (see Equation 1). The private cost includes the capital cost for initial investment, the fixed and variable operating and maintenance cost, and fuel cost. The social cost is the environmental and social costs measuring the impacts of energy consumption on the environment.

According to portfolio theory, there are two parameters: cost and its risk. The EPM is to find out the optimal cost-risk combination with either minimal cost at a given level of variance, or lowest risk at a given level of return. The cost for each component will be gathered from the historical data, and their standard deviation will be used to measure its risk. To minimize the overall energy cost, optimization techniques will be applied to the EPM model to seek the optimal energy combination.

Assumptions:

1) No bias for RPS, that means the consumption percent of renewable energy could be any amount depending on the market demand (traditional energy should have no priority than renewable energy);
2) The market is perfect, free, and no government intervention. In the free market, the price of all the energy resources will follow the demand and supply theory;

Under these assumptions, applying portfolio theory which derived from financial investment discipline to energy sectors becomes feasible. Based on the portfolio theory, this research is trying to find out an optimal portfolio solution for energy consumption in order to minimize the energy cost and risk combination.

4.3 EPM Social Cost

Social cost of energy is the cost that pays for the energy consumption, especially from environmental and social perspective. For example, the pollution and environmental impacts from burning the energy-related fuels, such as the climate change, the global warming, and human health harms. Table 4-1 shows a summary of the emissions or byproducts from burning the certain type of energy resources, and their impacts.

Energy Resource	Emission / Byproducts	Environmental Impacts	Health Impacts
Petroleum	CO_2, CO, SO_2, NO_x, PM, lead and air toxics	Yes (Global warming, climate change)	Yes (Cause human health problem)
Coal	SO_2, NO_x, CO_2, particulates, Mercury & other heavy medal, fly& bottom ash	Yes (Global warming, climate change)	Yes
Natural Gas	CO_2, CO, SO_2, NO_x	Yes	N/A
Nuclear	No carbon dioxide, but produce radioactive wastes	No	Yes (severe safety and security problems)

Table 4-1: Energy Social Cost: Environment and Health Impacts

Coal vs. Natural gas

Emissions from different types of energy sources are various; Table 4-2 shows EIA emissions analysis of CO_2 and carbon emissions coefficients for fossil fuels, and illustrates that burning coal will produce more carbon dioxide than petroleum and natural gas. Petroleum is the dirties energy resource, followed by coal, and natural gas is a relative clean resource, for example, over 200 pounds of carbon dioxide are produced per million Btu of coal compared to 160 pounds of CO_2 per million Btu of petroleum, and 117 pounds of CO_2 per million Btu of natural gas (EIA, "natural gas the environment").

	CO_2 Emissions Coefficients	**Carbon Emissions Coefficients**
	Million Metric Tons CO_2 per Quadrillion Btu	Million Metric Tons Carbon per Quadrillion Btu

	Petroleum[1]	Coal[2]	Natural gas[3]	Petroleum[4]	Coal[5]	Natural gas[6]
1980	73.04	95.53	53.06	19.92	26.05	14.47
1990	73.91	95.03	53.06	20.16	25.92	14.47
2000	74.19	95.35	53.06	20.23	26.00	14.47
2007	74.54	95.35	53.06	20.33	26.00	14.47
2008	74.54	95.35	53.06	20.33	26.00	14.47

Table 4-2: U.S. Emission Coefficients by energy source[7]

Natural gas has been considered a good alternative choice for petroleum and coal in the sense of greenhouse gas (GHG) emission; however, natural gas has some potential harm to human health, a recent study from Duke University researchers (Osborn et al., 2011) has tested 68 water wells located within half a mile of natural gas wells in Pennsylvania and New York, found potentially toxic levels of methane in 85% of drinking water near natural gas wells, and they showed systematic evidence for methane contamination of drinking water associated with shale-gas extraction. Therefore, whether natural gas is a clean energy is hard to say since there may be some unidentified potential harms, and coal still remains the major consumption because of the huge amount of availability and lower price.

Nuclear

[1] Emissions from crude oil
[2] Emissions from coal in residential& commercial sectors
[3] Emissions from pipeline natural gas
[4] Emissions from crude oil
[5] Emissions from coal in residential& commercial sectors
[6] Emissions from pipeline natural gas
[7] Source: Energy Information Administration: Emission Factors (per Quadrillion Btu)

Nuclear, as a newer energy resource, is a relatively cheap resource compared to petroleum, natural gas and coal, and has been considered to be cleaner than fossil fuel because of no carbon dioxide emissions from nuclear. However, researches regarding the safety of using nuclear fuel have shown that nuclear may not be a better choice considering the potential safety and security issues, for example, environmental impacts caused by nuclear radiation and wastes released into the atmosphere, accidents caused by unwanted events (such as floods, hurricane, earthquake, etc.) or operations (ExternE, 2005). Kopytko and Perkins (2011) have examined the effects of using nuclear power on the ability of human society and ecosystem to adapt to climate change using five criteria, and results showed that adapting nuclear power would either increase expenses for construction and operation or incur significant costs to the environment and public health and welfare, and thus nuclear power would not be a optimal mitigation to reduce greenhouse gas emission for climate change.

Social Cost of Carbon

Because of the variety of energy impacts on the environment and society, it's difficult to measure and estimate the social cost for each energy source. One way of measure the social cost is to estimate through carbon tax which has been used in some countries, especially in European countries. Carbon tax is composed according to the carbon content of fossil fuels, and that is considered more cost effective than energy tax[1] in terms of CO_2 reduction (Zhang &Baranzini, 2004, Manne & Richels (1993). Carbon

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[1] Energy tax is an excise tax imposed on both fossil fuels and carbon-free energy sources, such as nuclear energy, according to their energy (or heat) contents, which is defined as a fixed absolute amount of, e.g., US$ per Terajoule, per British thermal units, or per kilowatt-hour.

taxes can reduce CO2 emissions through both their price mechanism effects on energy consumption and fuel choice. A carbon tax can also be translated into a CO_2 tax, since a tonne of carbon corresponds to 3.67 tonnes of CO_2.

Another common used way is to estimate the costs of the carbon emissions using social cost of carbon (SCC). According to United States Department of Energy (IWG, 2010), social cost of carbon (SCC) is the estimate the monetized damages associated with an incremental increase in carbon emissions in a given year, including health impacts, economic dislocation, agricultural changes, and other effects that climate change can impose on humanity; in other words, SCC estimates the benefit to be achieved by avoiding the damage caused by each additional metric ton (tonne) of carbon dioxide (CO_2) put into the atmosphere considering CO_2 alone accounts for roughly 70% of the climate effects from greenhouse gases (Bell & Callan, 2011). According to economic theory, if SCC estimates were complete and markets perfect, a carbon tax should be set equal to the SCC; however, in reality, markets are not perfect, and SCC estimates are not complete (Yohe et al., 2007:823).

In the case of United States, there's no nationwide carbon tax, although a few states have introduced the tax, such as Colorado, California and Maryland. Instead, the U.S. government has created an interagency working group (IWG) to standardize the estimated of SCC, the report from IWG recommended a rage of SCC values: $5[1], $21[2],

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[1] Estimate at 5 percent discount rate;
[2] Estimate at 3 percent discount rate;

\$35[1] and \$65[2] per tonne of carbon dioxide (in 2007 dollars) based on three integrated assessment models (DICE[3], PAGE[4] and FUND[5]) and a "central" estimate of \$21 per ton of CO_2 in 2010, roughly 20 cents per gallon of gasoline (Ackerman & Stanton, 2010), and SCC tended to grow over time and will rise to \$30 per ton of CO_2 in 2025 and \$45 per ton of CO_2 in 2050 (IWG, 2010). However, research from E3Network (Ackerman & Stanton, 2011) argues the SCC estimate of U.S. government by IWG is flawed (too low) and the true social cost of carbon should be more uncertain than the government's \$21 per ton estimate, and they estimated the range of SCC for 2010 from \$28 to \$893 per ton of CO_2 according to DICE model (Table 4-3).

	U.S. Government By Interagency Working Group (IWG) (\$ per metric ton of CO_2)	**E3 Network estimate** by Ackerman & Stanton (\$ per metric ton of CO_2)
2010	\$21 /tCO_2 (\$5- \$65/tCO_2)	\$28 to \$893 /tCO_2
2050	45/tCO_2 (\$16-\$136/tCO_2)	\$1,550/tCO_2

Table 4-3: U.S. Social Cost of Carbon (SCC) Estimates

EPM Social Cost

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[1] Estimate at 2.5 percent discount rate;
[2] Represents the 95th percentile SCC estimate at a 3 percent discount rate, represents higher-than-expected impacts from temperature change further out in the tails of the SCC distribution.
[3] The Dynamic Integrated Climate Change(DICE) model was developed at Yale University by William Nordhaus, David Popp, Zili Yang, Joseph Boyer, and colleague.
[4] The Policy Analysis of Greenhouse Effect (PAGE) model was designed by Dr. Chris Hope, Reader in Policy Modeling at University of Cambridge Judge Business School.
[5] The Climate Framework for Uncertainty, Negotiation and Distribution (FUND) was developed by Richard Tol and
David Anthoff.

Considering all the impacts on the environment and the society from energy consumption, the social costs ($/Btu) will be addressed in the EPM model to capture the true energy cost; EPM social costs for energy resources are calculated by CO_2 Emissions Coefficients (Table 4-2) multiplying the social cost of carbon estimate (Table 4-3). The U.S. official SCC estimates by IWG will be used instead of E3Network estimates in the EPM social cost calculation. Table 4-4 shows the low, central and high social cost estimates for petroleum, coal and natural gas. The average central estimates of social cost are $1.57, $2 and $1.11 for petroleum, coal and natural gas, respectively; and higher social cost for petroleum, coal and natural gas are $4.85, $6.2 and $3.45 if there are high-than-expected impacts from temperature change.

The SCC estimates show that coal has the highest social cost compared to petroleum and natural gas, and this may change the energy consumption structure since coal will not be the cheapest energy resource considering the social cost. Energy portfolio may be different based on the structure of energy costs; therefore EPM will consider both the private and social cost, and the EPM simulation will be separately discussed with and without social costs.

	Petroleum	**Coal**	**Natural gas**
CO_2 Emissions Coefficients (Million Metric Tons CO_2 per Quadrillion Btu)	74.54	95.35	53.06
SCC Estimate_ Low ($ per metric ton of CO2)	$5/t$CO_2$	$5/t$CO_2$	$5/t$CO_2$
SCC Estimate_ Central ($ per metric ton of CO2)	$21/t$CO_2$	$21/t$CO_2$	$21/t$CO_2$
SCC Estimate_ High	$65/t$CO_2$	$65/t$CO_2$	$65/t$CO_2$

($ per metric ton of $CO2$)			
EPM Social Cost(SC)_Low ($/Million Btu)	$0.37	$0.48	$0.27
EPM Social Cost(SC)_Central ($/Million Btu)	$1.57	$2.00	$1.11
EPM Social Cost(SC)_High ($/Million Btu)	$4.85	$6.20	$3.45

Table 4-4: EPM Social Cost Estimates

4.4 EPM Conceptual Framework

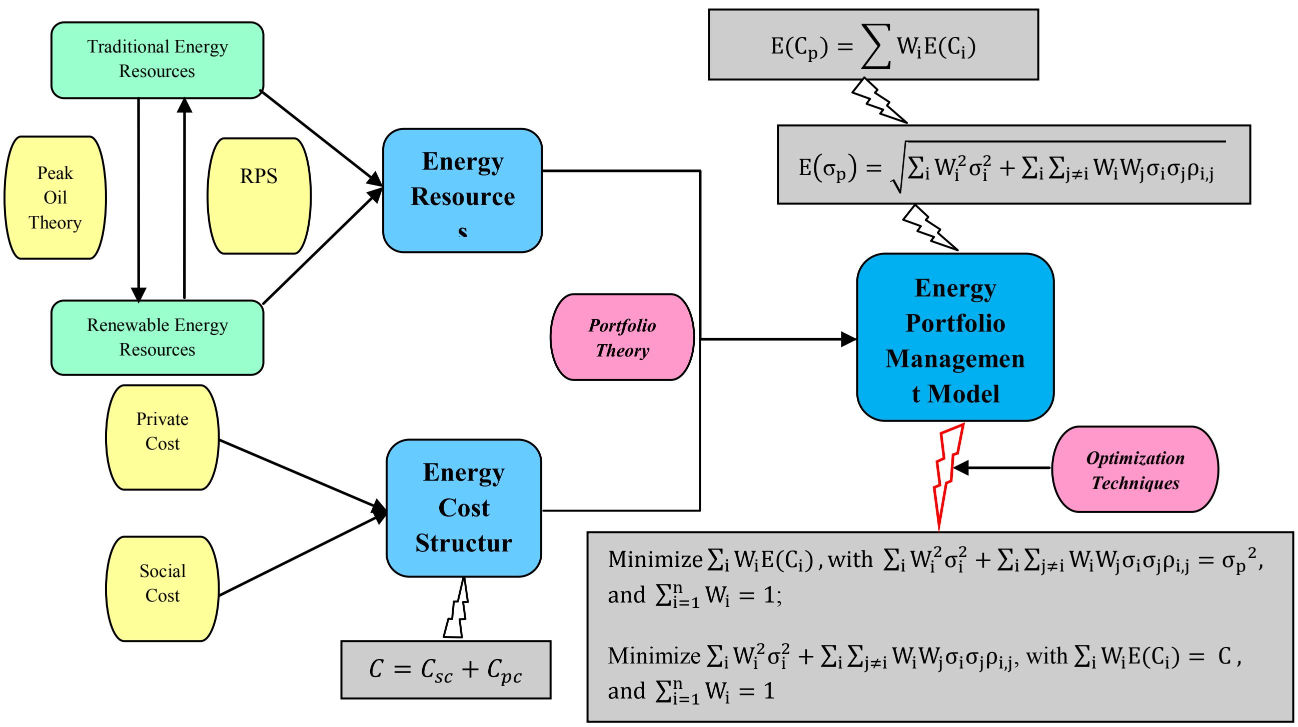


Figure 4-1: Energy Portfolio Management Model

Cost Structure:

$$\sum_{min} C = \sum_{i=1}^{n} (C_{sc_i} + C_{pc_i})_i \quad \text{-------------------} \ (1)$$

$$C_{sc} = social\ cost\ for\ energy\ i;$$

$$C_{pc} = private\ cost\ for\ energy\ i;$$

i = 1 …n, energy resources.

The expected portfolio cost $E(C_p)$:

For n energy resources: $E(C_p) = \sum_i W_i E(C_i)$ ------------------- (2)

Where:

W_i are the percentage of the energy i in the portfolio, and $\sum_{i=1}^{n} W_i = 1$

The expected portfolio risk $E(\sigma_p)$:

For n energy resources: $E(\sigma_p) = \sqrt{\sum_i W_i^2 \sigma_i^2 + \sum_i \sum_{j \neq i} W_i W_j \sigma_i \sigma_j \rho_{i,j}}$ -----------(3)

Where:

W_i : the percentage of energy resource i in the portfolio;

σ_i : the standard deviations of energy resources i;

ρ_{ij}: the correlation coefficient between energy costs on energy resource i and j;

To apply the MVP, it has three components: expected portfolio cost, expected portfolio risk and the correlation coefficient. According to these researches, each individual technology actually consists of a portfolio of cost streams, such as capital, operating and maintenance, fuel and CO_2 costs (Roques et al., 2006; Lesser et al., 2007; Rodoulis, 2010). In this research, the cost factors are categorized into private cost for production and social cost. The private cost includes the capital cost, the fixed and variable operating and maintenance cost, and fuel cost. The social cost will be also included to measure the cost of the impacts on the environment. The standard deviation for each cost component will be used as the measurement of its risk.

EPM Framework Working Flow:

1) Identify and list the energy resources which are available in the specific area;
2) Define the cost factors and components for each energy resource;
3) Gather the cost data from the history;
4) Enter the input parameters (energy costs) into the EF software: Crystal Ball with OptQuest from Oracle, or @RISK with Risk Optimizer from Palisade;
5) Define the formula for calculating the portfolio cost and risk;
6) Simulate the model based on the input parameters and formula;
7) Find out the optimal cost-risk combination, and identify the Efficient Frontier.

The EPM framework provides a step-by-step guidance for energy consumers about how to manage and find out the optimal consumption plan. The objectives of EPM model are to identify the optimal cost-risk combination at different level of cost or risk; and provide some possible solutions to improve your current status close to the optimal point. Regulators, policy makers, and consumers (corporate or individual) can use the EPM model to measure the consumption of energy.

Chapter 5 EPM Simulation: the case of United States

Applying the EPM model on the U.S. energy industry, the first step is to find out the energy cost for each energy resource; then simulate the optimal energy portfolio solution for providing the lowest portfolio cost and associated portfolio risk using the optimization tool called Crystal Ball from Oracle.

In order to get the comparable energy cost, each energy cost has to use the same unit: dollars per million Btu. Data are collected from Annual Energy Review of U.S. Energy Information Administration, covers energy consumer price from 1970 to 2007 as a proxy of energy cost (see Appendix 3). Due to data limitation, only major energy resources have been included, such as coal, natural gas, petroleum, nuclear and biomass. Wind and solar are not included in this simulation, because of its limited usage compared to other energy resources. Petroleum has been used instead of crude oil in the EPM simulation, because this research aims to provide guidance for energy consumers; therefore, only final energy products are considered, and their consumer price are used as the proxy of energy cost.

There are two sampling methods in Crystal Ball: Monte Carlo and Latin Hypercube sampling simulation. Monte Carlo simulation randomly selects a valid value from each assumption's defined distribution, while Latin Hypercube randomly selects values but spreads the random values evenly over each assumption's defined distribution (Crystal Ball Reference Manual). Latin Hypercube sampling is considered more precise than Monte Carlo sampling because using Latin Hypercube the entire range of distribution is sampled more evenly and consistently, therefore, the EPM simulation will use Latin

Hypercube sampling simulation instead of Monte Carlo simulation and run 1000 simulations with 500 trials for each case.

5.1 EPM Simulation by Source

5.1.1 EPM Simulation Parameters

Energy Cost

In the case of United States, EPM model will simulate based on available data covering the energy cost from 1970 to 2007 for five energy recourse: coal, natural gas, petroleum, nuclear fuel and biomass (Appendix 3). Figure 5-1 shows the consumer prices for each energy source, and the prices are used as a proxy of energy cost, because consumer prices are more reasonable to capture the real portfolio cost for energy consumers.

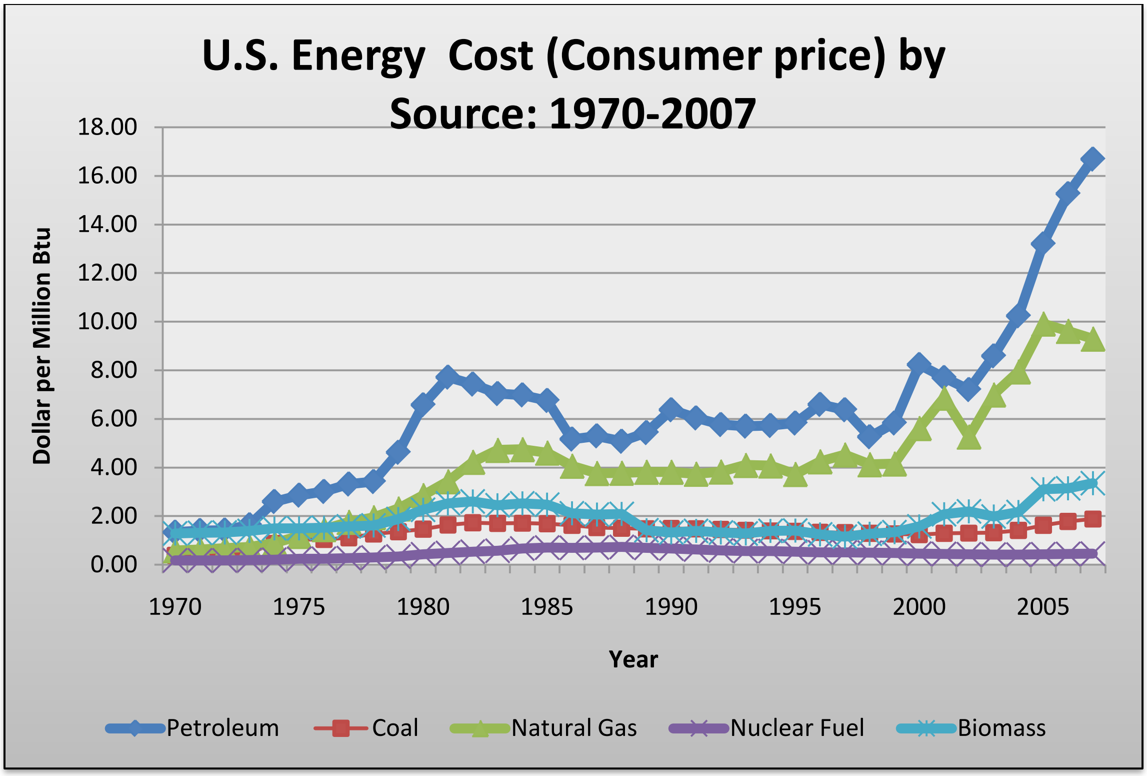


Figure 5-1: U.S. Energy Cost (Consumer Price) by Source: 1970-2007 (EIA ARE)

	Petroleum	Coal	Natural Gas	Nuclear Fuel	Biomass
Mean	6.20	1.32	4.06	0.46	1.85
SD	3.39	0.37	2.42	0.17	0.60
Min	1.33	0.38	0.59	0.18	1.15
Max	16.70	1.88	9.92	0.73	3.35

Table 5-1: Statistics for Energy Cost by Source

Table 5-1 shows some basic statistics from data analysis, and mean and standard deviation will be needed for setting up the distributions for each energy resource. Table 5-2 is the results from Crystal Ball data analysis, and it summarizes the mean of energy costs and their correlations. Energy cost sensitivity analysis is also available in the Appendix 4.

	Petroleum	Coal	Natural Gas	Nuclear Fuel	Biomass

Mean	6.20	1.319210526	4.056315789	0.463947368	1.845789
Correlations:					
Petroleum	1.0000	0.6450	0.8882	0.3187	0.5828
Coal		1.0000	0.5662	0.7231	0.6362
Natural Gas			1.0000	0.3858	0.4546
Nuclear Fuel				1.0000	0.1200
Biomass					1.0000

Table 5-2: Energy Cost Correlations from Crystal Ball

Energy Cost Distribution

To simulate the model using OptQuest in the Crystal Ball, the distributions for energy costs are needed. Running data analysis in the Crystal Ball will generate a distribution that fits the sample. Figure 5-2, 5-3, 5-4, 5-5, 5-6 illustrate the best fits of distribution for coal, natural gas, petroleum, nuclear fuel and biomass are min extreme distribution, logistic distribution, logistic distribution, beta distribution and gamma distribution, respectively.

Data analysis in the Figure 5-2 shows the probability distribution of coal is skewed to the left where most of data are near the maximum rate, therefore the best fit for coal is minimum extreme distribution, a negatively skewed form of the extreme value distribution. Minimum extreme distribution has two parameters: likeliest (m) and scale (s), the likeliest parameter (m) represents the most likely value for the variable (the highest point on the probability distribution or mode), the scale parameter can be estimated by the formula: $s = \sqrt{\frac{6*variance}{\pi^2}}$. In this case, according to the statistic results of coal, the values for parameters are: m (likeliest) = 1.27, s (scale) = 0.29. Therefore, the distribution for coal has been defined in the Figure 5-3.

The function of the distribution for coal is:

$$f(x) = \frac{1}{s}\left(e^{\frac{x-m}{s}}\right)e^{-e^{\frac{x-m}{s}}} = \frac{1}{0.29}\left(e^{\frac{x-1.27}{0.29}}\right)e^{-e^{\frac{x-1.27}{0.29}}}$$

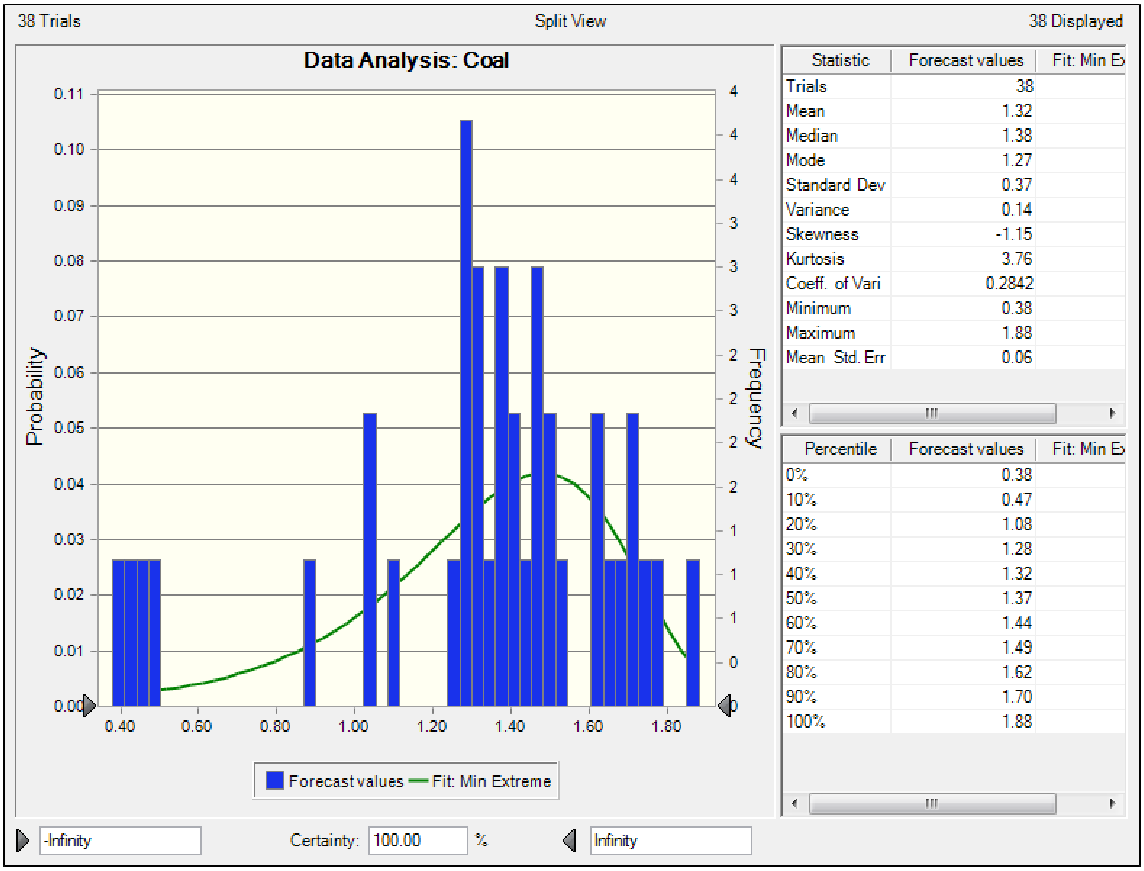


Figure 5-2: Data Analysis for Coal

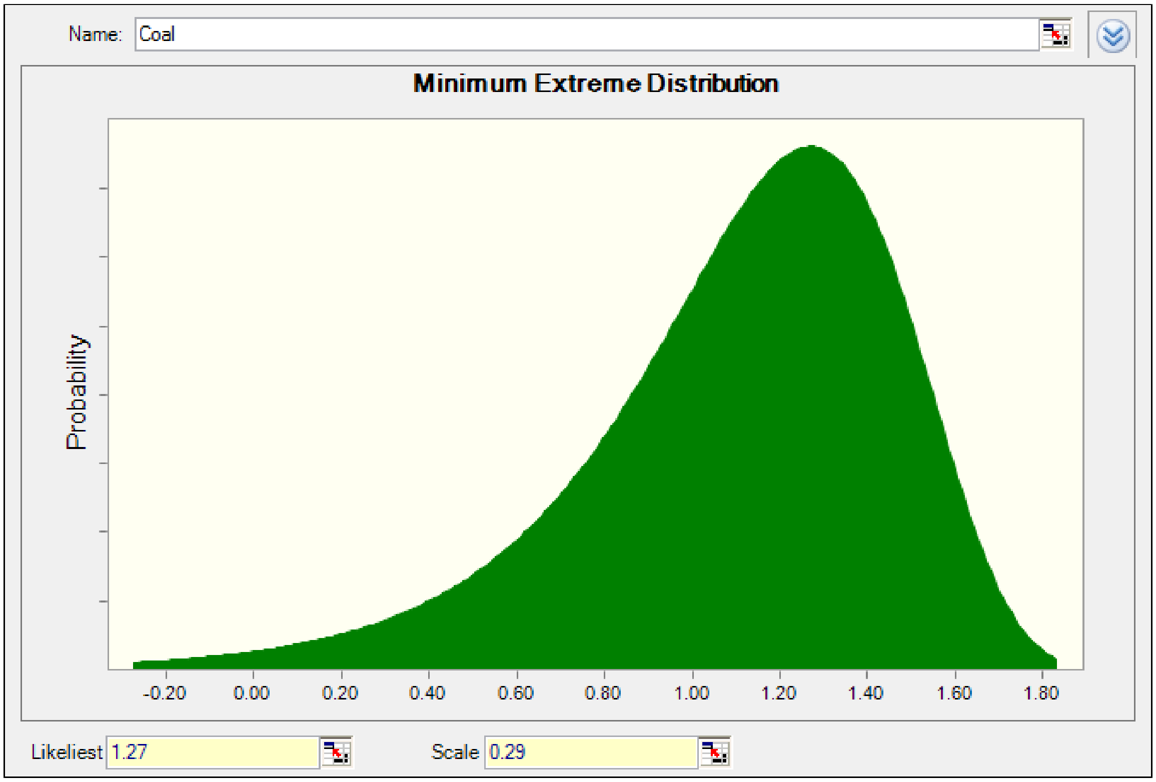


Figure 5-3: Distribution Assumption for Coal

Data analysis in the Figure 5-4 shows that the probability distribution of natural gas is continuous shape with a higher kurtosis (the peakedness of a distribution); therefore the best fit for natural gas is logistic distribution other than normal distribution. The parameters for logistic distribution are: mean (μ) and scale (s), the mean parameter is the average of a set of values; the scale parameter can be estimated by the formula: $s = \sqrt{\frac{3*variance}{\pi^2}}$. In this case, according to the statistic results of natural gas, the values for parameters are: μ (mean) = 4.06, s (scale) = 1.33, therefore, the distribution for natural gas has been defined in the Figure 5-5.

The function of the distribution for natural gas is:

$$f(x) = \frac{e^{-(\frac{x-\mu}{s})}}{s(1+e^{-(\frac{x-\mu}{s})})^2} = \frac{e^{-(\frac{x-4.06}{1.33})}}{1.33(1+e^{-(\frac{x-4.06}{1.33})})^2}$$

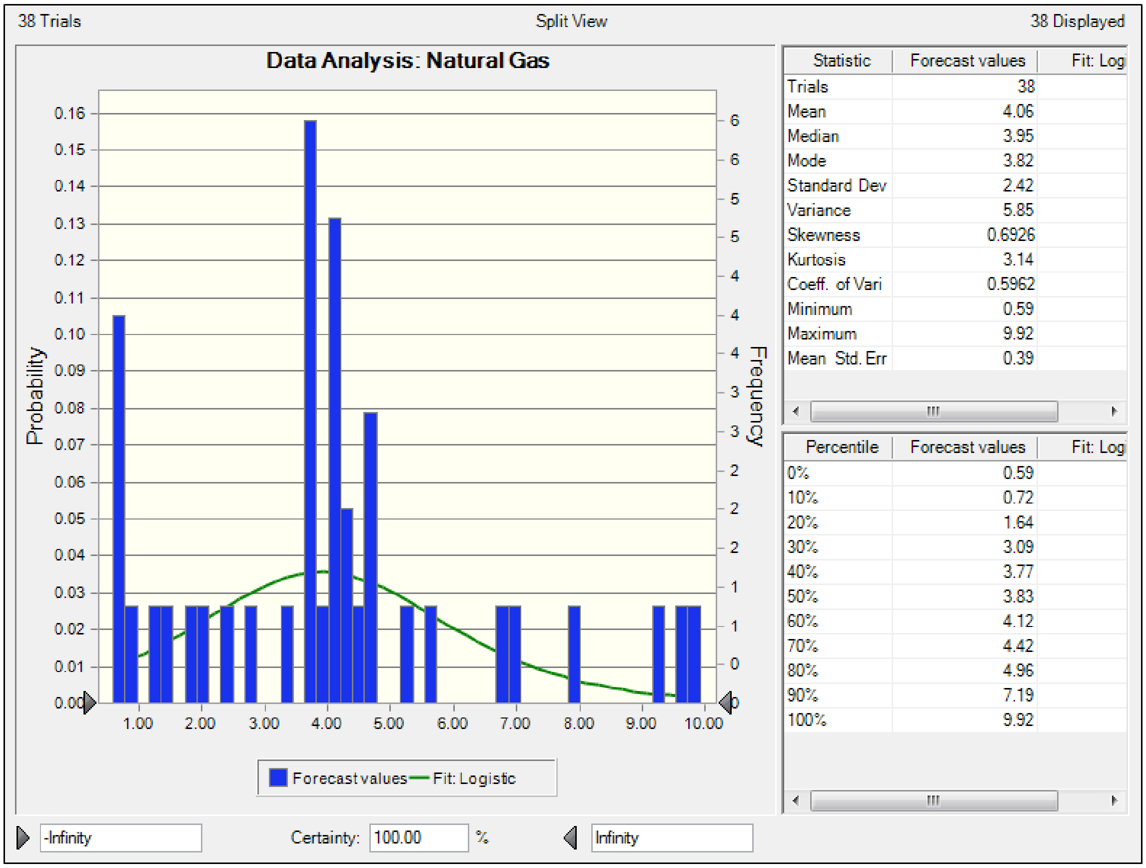


Figure 5-4: Data Analysis for Natural Gas

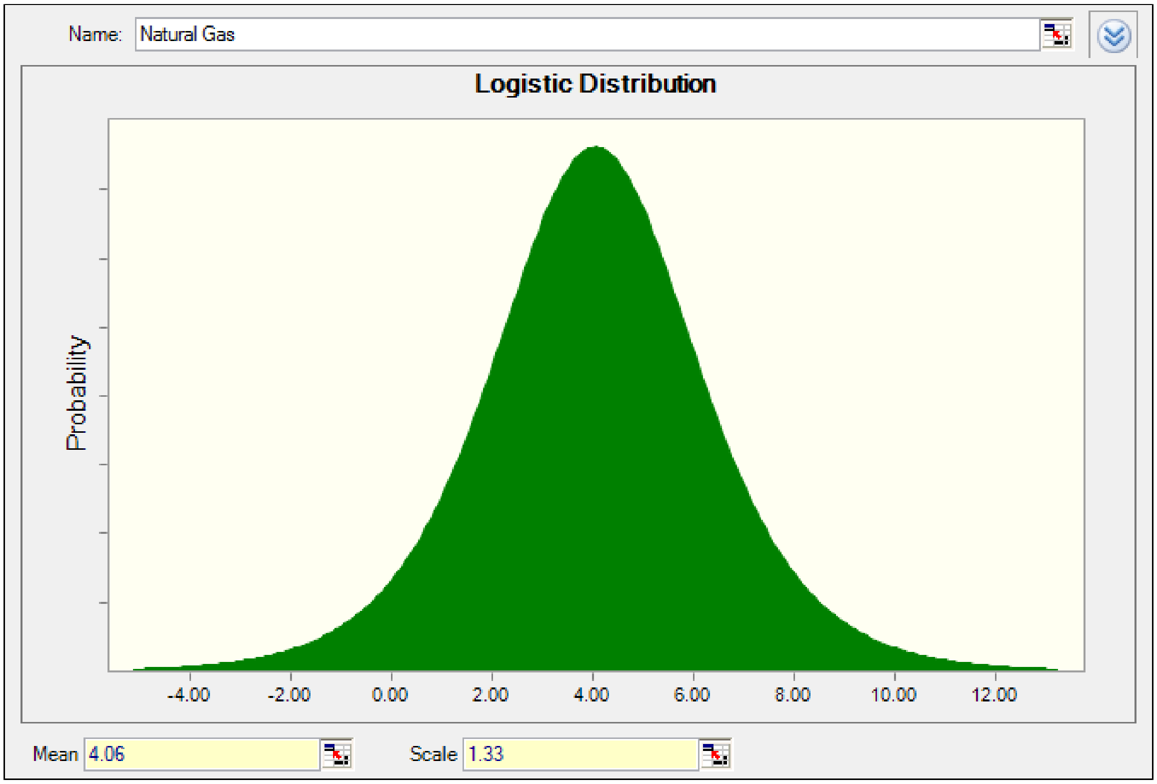


Figure 5-5: Distribution Assumption for Natural Gas

Data analysis in the Figure 5-6 shows that the probability distribution of petroleum is continuous curve with a higher kurtosis (the peakedness of a distribution); therefore the best fit for petroleum is logistic distribution other than normal distribution. The parameters for logistic distribution are: mean (μ) and scale (s), the mean parameter is the average of a set of values; the scale parameter can be estimated by the formula: $s = \sqrt{\frac{3*variance}{\pi^2}}$. In this case, according to the statistic results of petroleum, the values for parameters are: μ (mean) = 6.02, s (scale) = 1.87, therefore, the distribution for petroleum has been defined in the Figure 5-7.

The function of the distribution for petroleum is:

$$f(x) = \frac{e^{-(\frac{x-\mu}{s})}}{s(1+e^{-(\frac{x-\mu}{s})})^2} = \frac{e^{-(\frac{x-6.02}{1.87})}}{1.87(1+e^{-(\frac{x-6.02}{1.87})})^2}$$

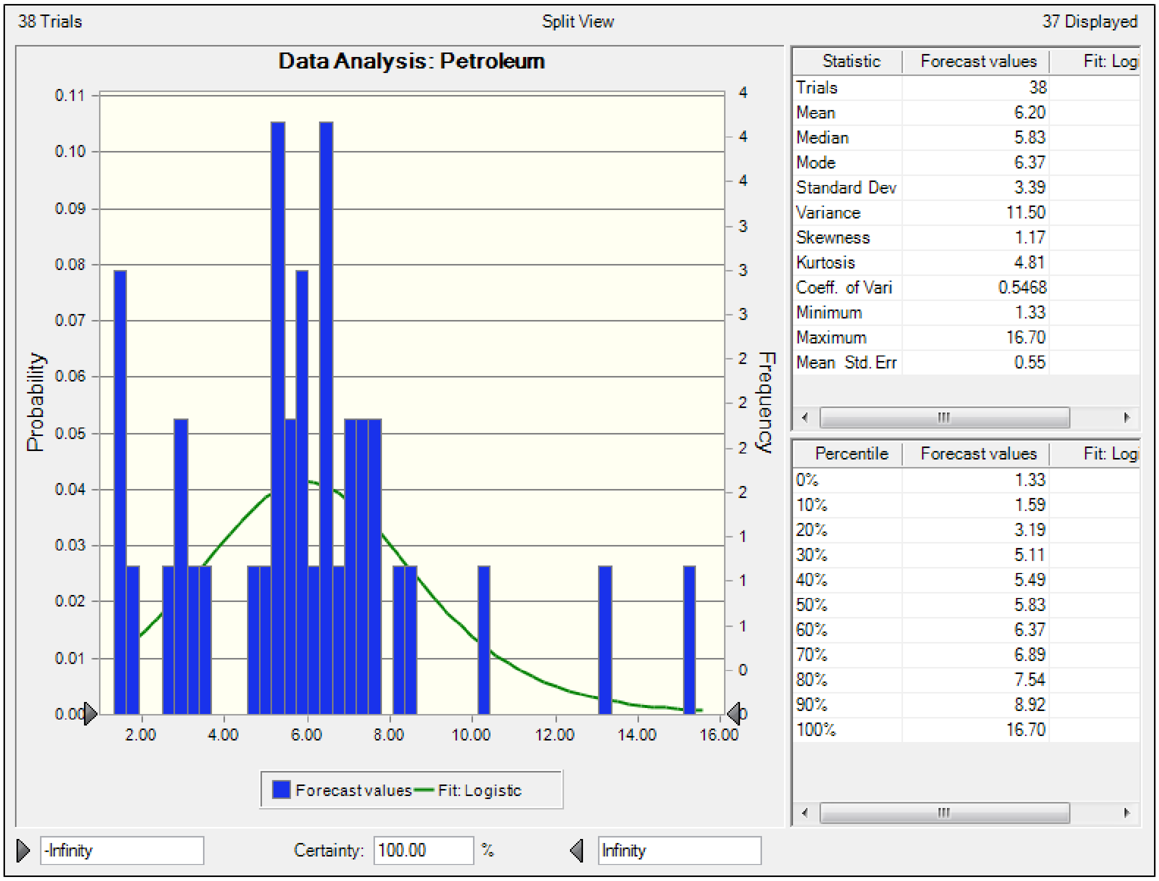


Figure 5-6: Data Analysis for Petroleum

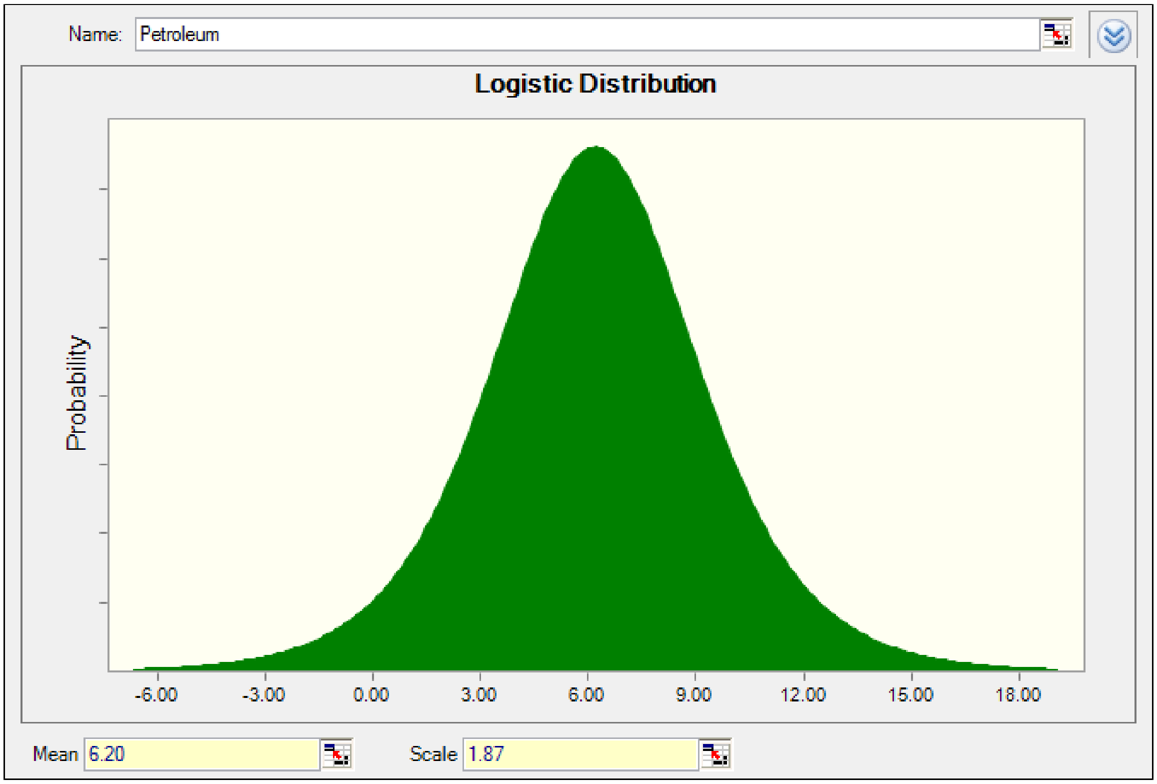


Figure 5-7: Distribution Assumption for Petroleum

Data analysis in the Figure 5-8 shows the probability distribution of nuclear is continuous and flexible within a fixed range, and most of data are near the maximum value, therefore, the best fit for nuclear fuel is beta distribution with greater alpha than beta. Beta distribution has four parameters: minimum, maximum, alpha (α) and beta (β). Minimum and maximum are the minimal and maximal, alpha and beta parameters are two positive values that define the shape of distribution. In this case, the values of alpha and beta are set to 3 and 2 in order to fit the shape in Figure 5-8, and min = 0.18, max = 0.73, therefore, the distribution for nuclear fuel has been defined in the Figure 5-9.

The function of the distribution for nuclear fuel is:

$$f(x) = \frac{\frac{x - min}{max - min}^{(\alpha-1)} \quad (1 - \frac{x - min}{max - min})^{(\beta-1)}}{\beta(\alpha, \beta)}$$

$$= \frac{\frac{x - 0.18}{0.73 - 0.18}^{(3-1)} \quad (1 - \frac{x - 0.18}{0.73 - 0.18})^{(2-1)}}{2(3,2)}$$

if $0 < x - min < max - min, \alpha, \beta > 0$, otherwise $f(x) = 0$

where: $\beta(\alpha, \beta) = \frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha,\beta)}$, Γ is the Gamma function and Γ(n) = (n-1)!

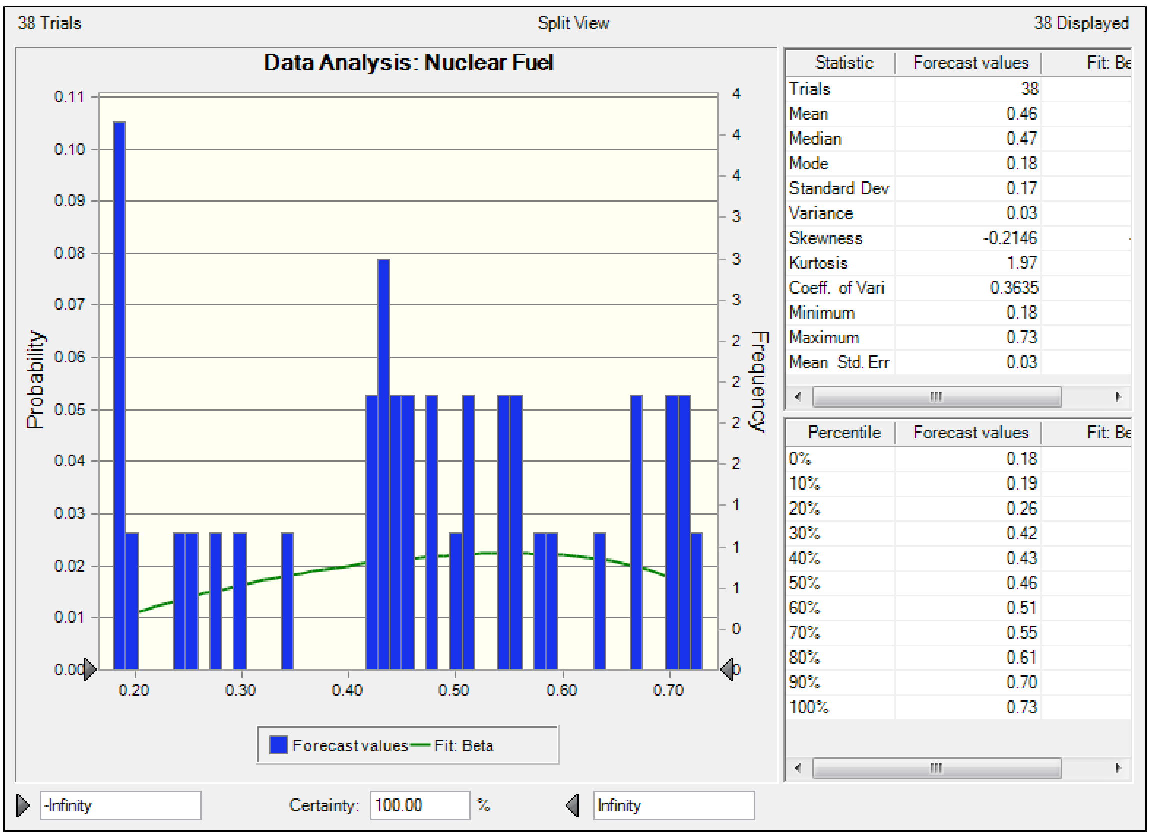


Figure 5-8: Data Analysis for Nuclear Fuel

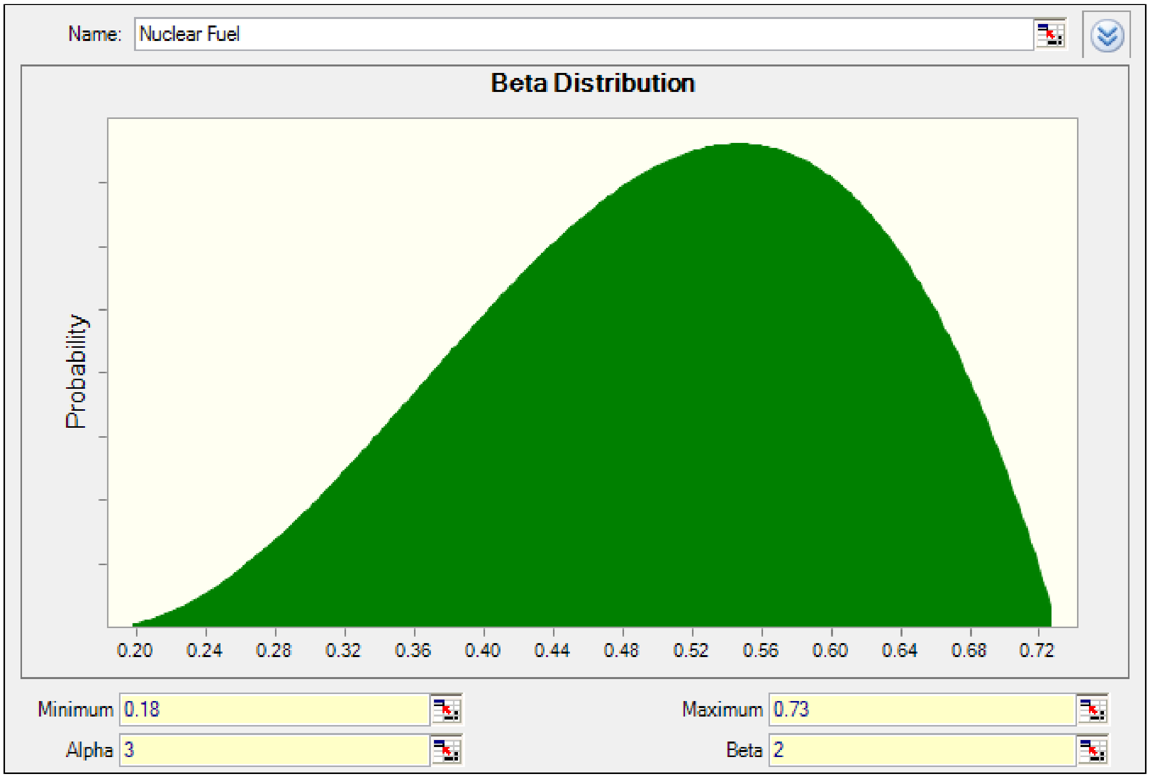


Figure 5-9: Distribution Assumption for Nuclear Fuel

Data analysis in the Figure 5-10 shows the probability distribution of biomass has a longer right tail and the mass of distribution is concentrated on the left side with relatively few high values, therefore the best fit for biomass is gamma distribution. Gamma distribution has three parameters: location (L), scale (s) and shape (β). Scale and shape can be estimated by the formula: $S = \frac{variance}{mean} = \frac{0.35}{1.85}$=0.19, $\beta = \frac{mean^2}{variance} = \frac{1.85^2}{0.35}$=9.6

If the scale and shape parameters are set to 0.19 and 9.6, the distribution will look like Figure 5-11, however it doesn't fit with the distribution from the historical data (Figure 5-10), therefore, in order to fit the data, the vales scale and shape are set to 0.3 and 2 instead of the values from the formula. In this case, the value of location parameter is set to 1.15, the minimal value, and the distribution assumption for biomass is in Figure 5-12.

The function of the distribution for biomass is:

$$f(x) = \frac{\frac{x-L}{s}^{\beta-1} e^{-\frac{x-L}{s}}}{\Gamma(\beta)s} = \frac{\frac{x-1.15}{0.3}^{2-1} e^{-\frac{x-1.15}{0.3}}}{0.3\Gamma(2)}$$

if $x > L, 0 < \beta < \infty, 0 < s < \infty$, where Γ is the Gamma function, and Γ(n) = (n-1)!

$$f(x) = 0 \text{ if } x \leq L$$

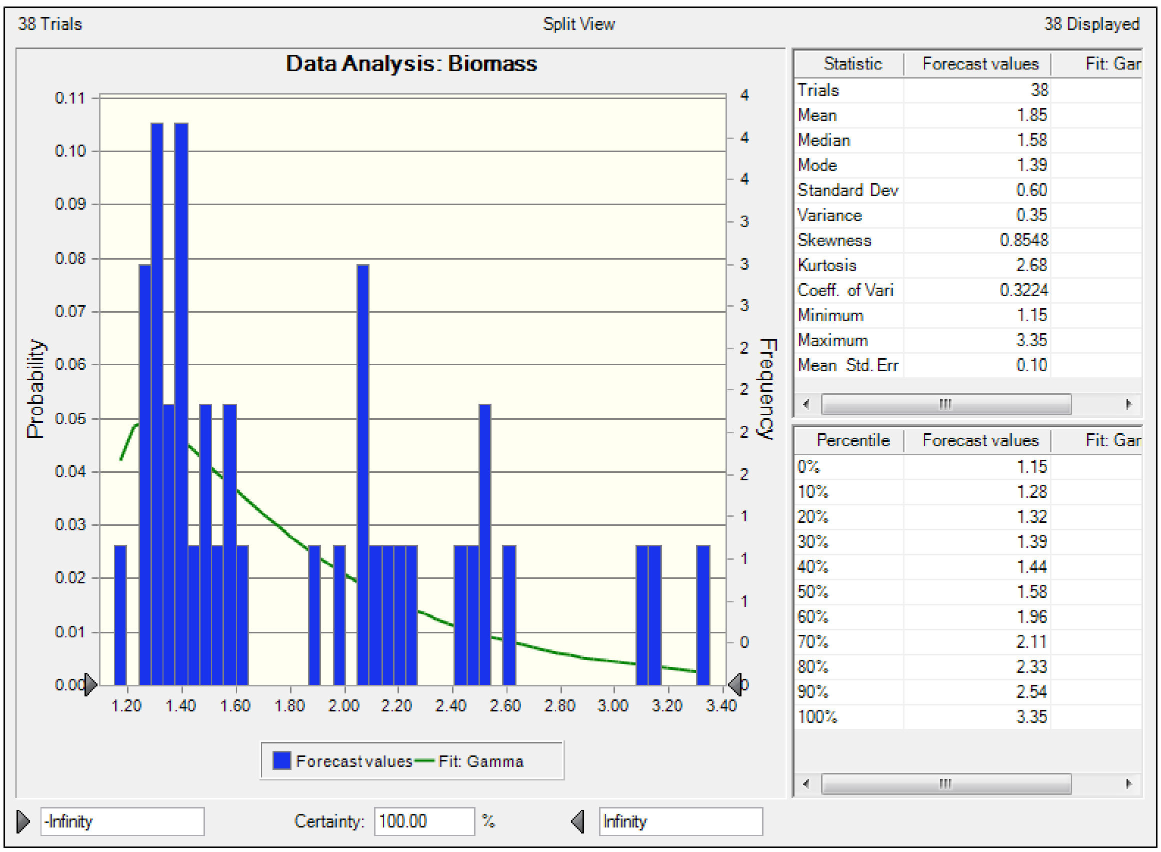


Figure 5-10: Data Analysis for Biomass

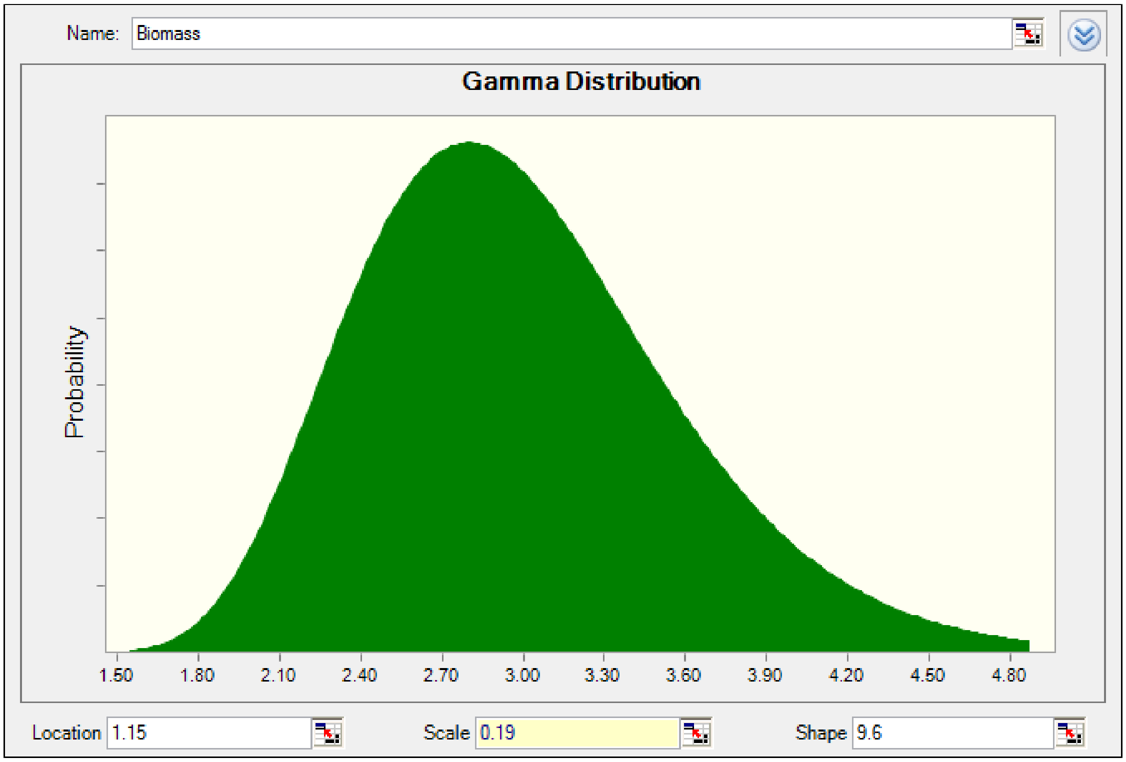


Figure 5-11: Distribution Assumption for Biomass

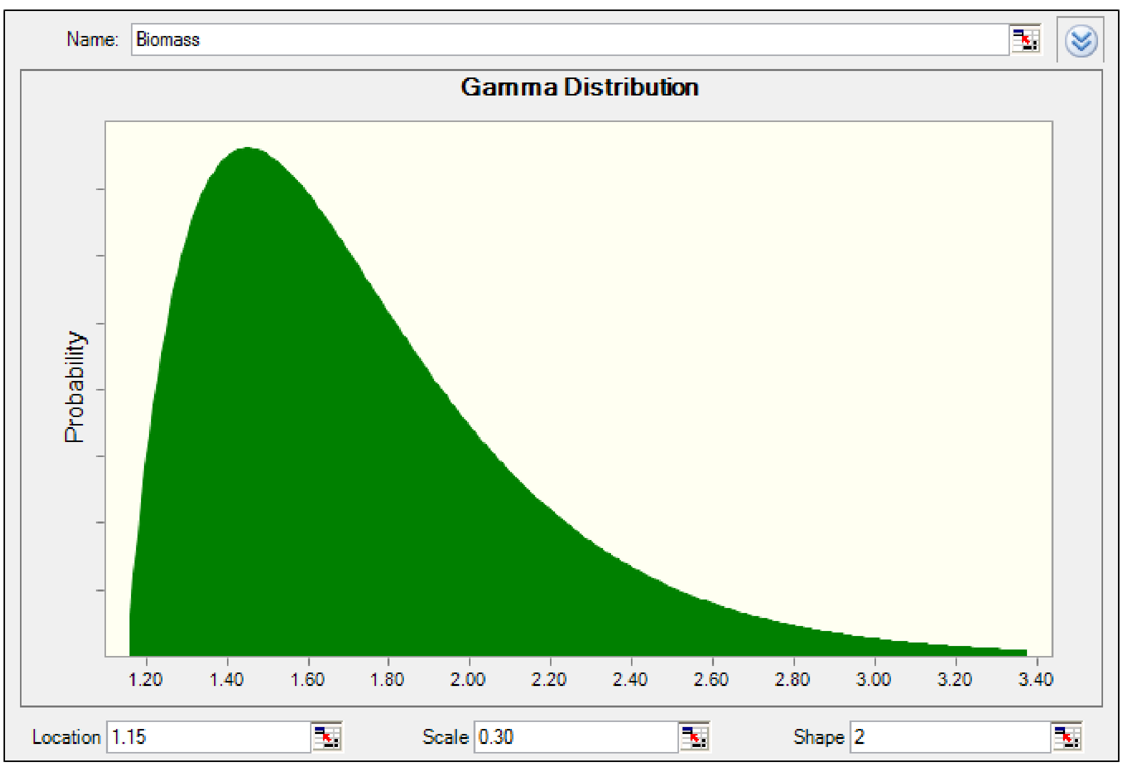


Figure 5-12: Distribution Assumption for Biomass

Energy Percentage Bound

Min and Max is based on Energy Information Administration Annual Energy Review "Primary Energy Consumption by Source, 1949-2009", lower and upper bounds are set up according to the min and max of consumption percentage, used as the bound parameter of each decision variable.

Percentage	Coal	Natural Gas	Petroleum	Nuclear Fuel	Biomass
Min	16.58%	16.09%	37.15%	0.00%	2.02%
Max	37.44%	32.43%	47.59%	8.83%	4.84%
Lower	10.00%	5.00%	10.00%	5.00%	1.00%
Upper	40.00%	35.00%	50.00%	15.00%	15.00%

Table 5-3: Energy Consumption (Percentage) Bound by Source: 1970-2007 (see Appendix 2)

5.1.2 Case Analysis

Case One

Objectives: Minimize the mean of portfolio cost

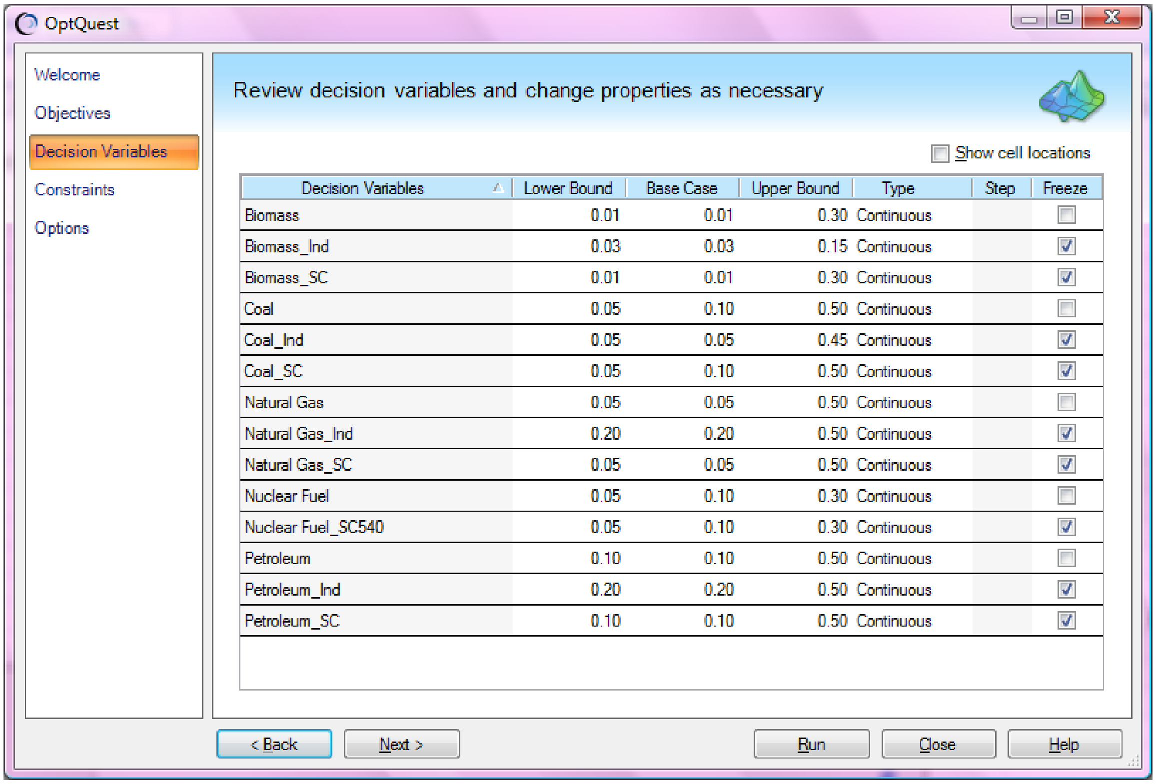
Requirement: the standard deviation of portfolio cost must be between 0.5 and 1.5

Efficient Frontier: vary the lower bound from 0.5 to 0.9 in steps of 0.01.

Decision Variables (Table 5-4, Figure 5-13):

Decision Variable	Lower Bound	Base Case	Upper Bound	Type
Biomass	0.01	0.01	0.30	Continuous
Coal	0.05	0.10	0.50	Continuous
Natural Gas	0.05	0.05	0.50	Continuous
Nuclear Fuel	0.05	0.10	0.30	Continuous
Petroleum	0.10	0.10	0.50	Continuous

Table 5-4: Decision Variable Bounds for Case One



Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☐
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☑
Coal	0.05	0.10	0.50	Continuous		☐
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC	0.05	0.10	0.50	Continuous		☑
Natural Gas	0.05	0.05	0.50	Continuous		☐
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☑
Nuclear Fuel	0.05	0.10	0.30	Continuous		☐
Nuclear Fuel_SC540	0.05	0.10	0.30	Continuous		☑
Petroleum	0.10	0.10	0.50	Continuous		☐
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☑

Figure 5-13: Decision Variable Bounds in the Crystal Ball OptQuest

Constraints: Biomass + Coal + Natural Gas + Nuclear Fuel + Petroleum = 1

The expected portfolio cost formula:

$$E(C_p) = W_c E(C_c) + W_{ng} E(C_{ng}) + W_p E(C_p) + W_n E(C_n) + W_b E(C_b)$$

Where:

$E(C_p)$ is their expected energy portfolio costs (Dollars per Million Btu).

W_c and $E(C_c)$ are the percentage and expect cost of coal in the portfolio,

W_{ng} and $E(C_{ng})$ are the percentage and expect cost of natural gas in the portfolio;

W_p and E (C_p) are the percentage and expect cost of petroleum in the portfolio;

W_n and E (C_n) are the percentage and expect cost of nuclear fuel in the portfolio;

W_b and E (C_b) are the percentage and expect cost of biomass in the portfolio;

and $W_c + W_{ng} + W_p + W_n + W_b = 1$

Optimization Option: run for 1000 simulations;

Software: Crystal Ball and OptQuest;

Data: Energy Cost (Consumer Price) by Source from Annual Energy Review of EIA.

Solution 1 results from OptQuest:

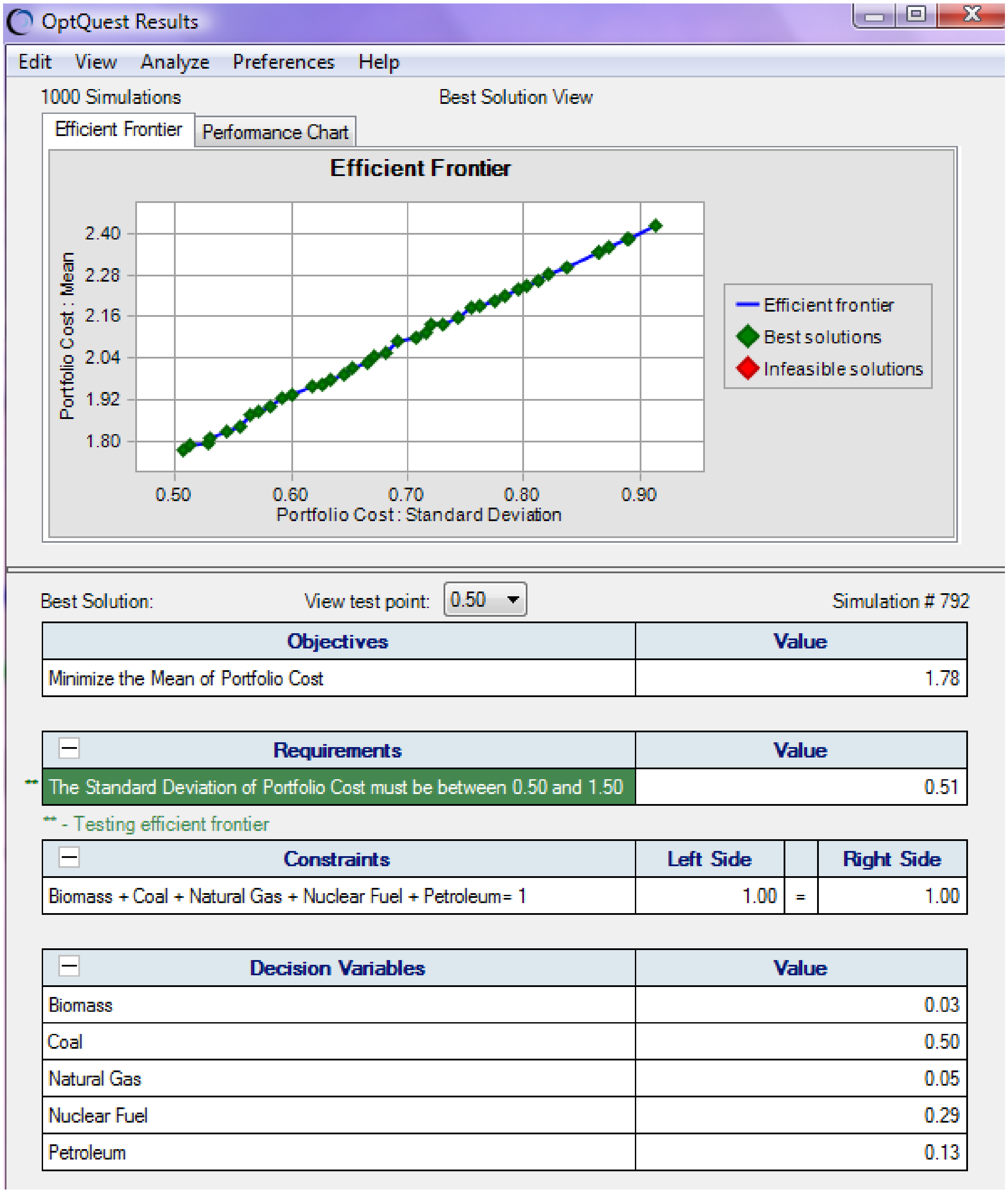


Figure 5-14: OptQuest Simulation Results for Solution 1

Solution 2 results from OptQuest:

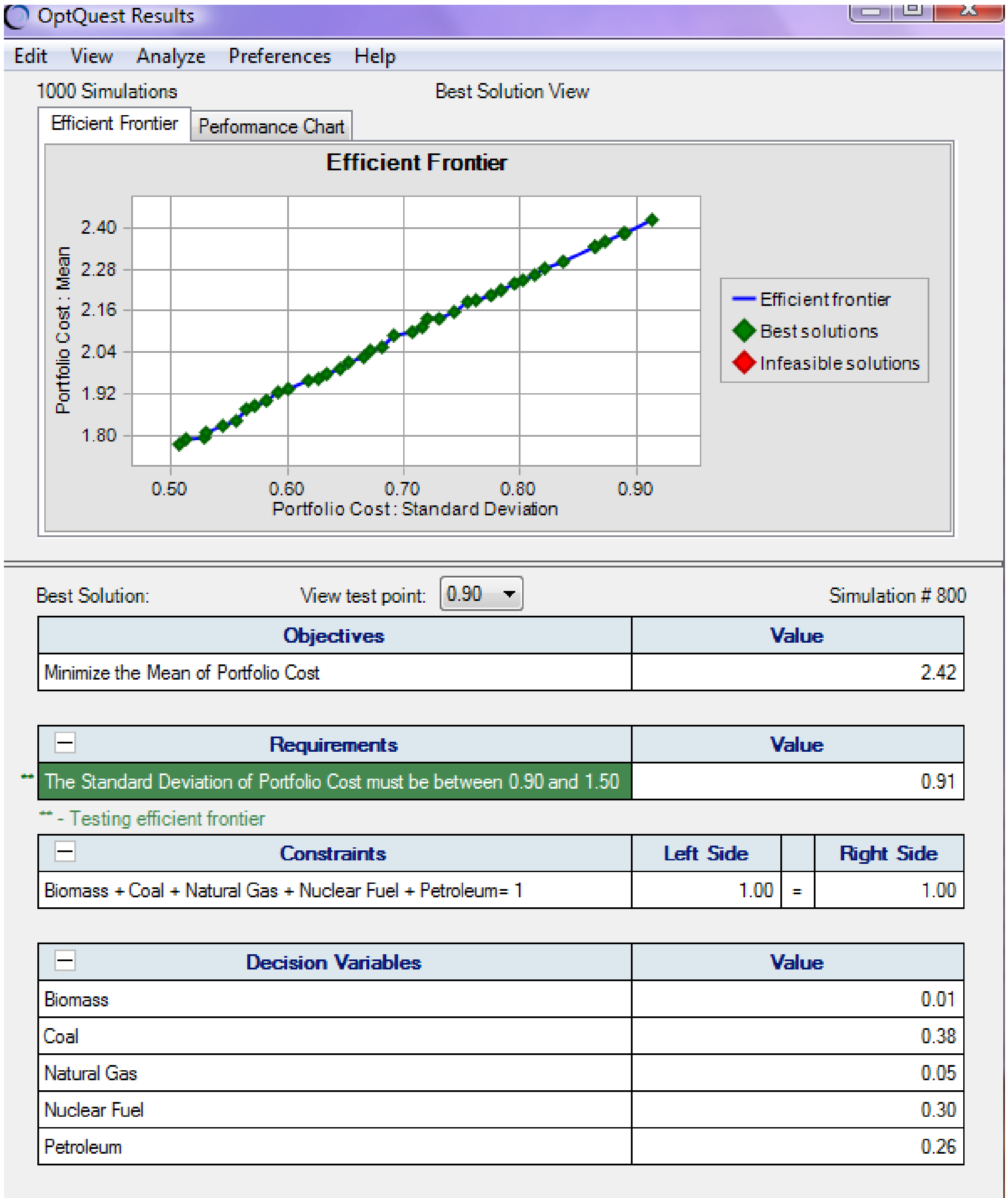


Figure 5-15: OptQuest Simulation Results for Solution 2

	Portfolio Cost	Portfolio Risk/SD	Biomass	Coal	Natural Gas	Nuclear Fuel	Petroleum
Best	$1.78	0.51	3.00%	50.00	5.00%	29.00%	13.00%

Solution 1				%			
Best Solution 2	$2.42	0.91	1.00%	38.00 %	5.00%	30.00%	26.00%
Change (Solution 2 to Solution 1)	-26.45% (percentage)	-43.96% (percentage)	2.00%	12.00 %	0.00%	-1.00%	-13.00%

Table 5-5: Case One Results Comparison

Analysis: keeping the consumption of natural gas unchanged and increasing the percentage of coal and biomass usage by 12% and 2% respectively (from solution 2 to solution 1, Table 5-5), it will reduce petroleum consumption by 13% from 26% to 13% and nuclear fuel consumption by 1%, which will lower the portfolio cost by 26.45% from $2.42 per million Btu to $1.78 per million Btu with a decreasing of portfolio risk by 43.96% from 0.91 to 0.51.

Result:

1) Without considering the social cost, increasing the usage of petroleum and nuclear fuel, especially petroleum, will cause the significant increase of portfolio cost and its associated risk (Solution 2, Figure 5-15).
2) Without considering the social cost, increasing the usage of coal and biomass will reduce the portfolio cost and its associated risk, especially the usage of coal (Solution 1, Figure 5-14).
3) Without considering the social cost, coal and biomass are preferable compared to petroleum, and solution 1 is the optimal energy portfolio with a portfolio risk range from 0.5 to 0.9.

Case Two:

Objectives: Minimize the mean of portfolio cost

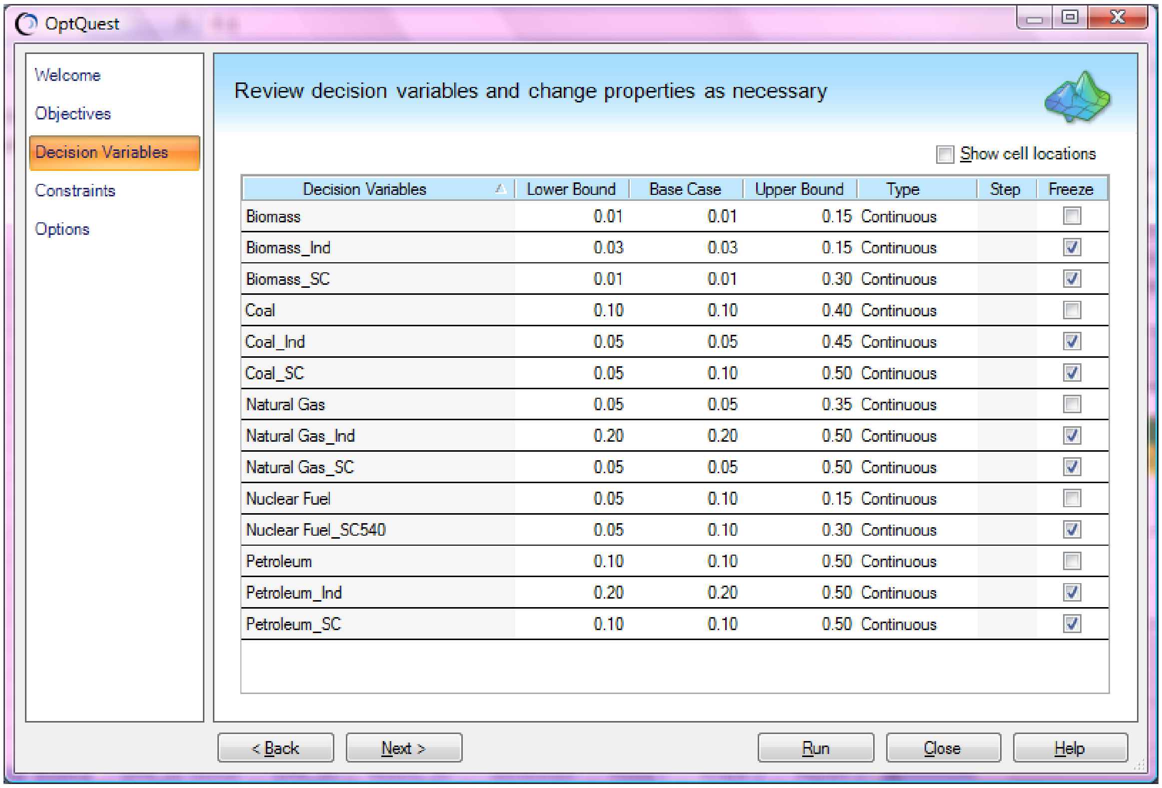
Requirement: the standard deviation of portfolio cost must be between 0.5 and 1.5

Efficient Frontier: vary the lower bound from 0.5 to 0.9 in steps of 0.01.

Decision Variables (Table 5-6, Figure 5-16):

Decision Variable	Lower Bound	Base Case	Upper Bound	Type
Biomass	0.01	0.01	0.15	Continuous
Coal	0.10	0.10	0.40	Continuous
Natural Gas	0.05	0.05	0.35	Continuous
Nuclear Fuel	0.05	0.10	0.15	Continuous
Petroleum	0.10	0.10	0.50	Continuous

Table 5-6: Decision Variable Bounds for Case Two



Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.15	Continuous		☐
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☑
Coal	0.10	0.10	0.40	Continuous		☐
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC	0.05	0.10	0.50	Continuous		☑
Natural Gas	0.05	0.05	0.35	Continuous		☐
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☑
Nuclear Fuel	0.05	0.10	0.15	Continuous		☐
Nuclear Fuel_SC540	0.05	0.10	0.30	Continuous		☑
Petroleum	0.10	0.10	0.50	Continuous		☐
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☑

Figure 5-16: Decision Variable Bounds in the Crystal Ball Optquest

Constraints: Biomass + Coal + Natural Gas + Nuclear Fuel + Petroleum = 1

The expected portfolio cost formula:

$$E(C_p) = W_c E(C_c) + W_{ng} E(C_{ng}) + W_p E(C_p) + W_n E(C_n) + W_b E(C_b)$$

Where:

$E(C_p)$ is their expected energy portfolio costs (Dollars per Million Btu).

W_c and $E(C_c)$ are the percentage and expect cost of coal in the portfolio,

W_{ng} and $E(C_{ng})$ are the percentage and expect cost of natural gas in the portfolio;

W_p and E (C_p) are the percentage and expect cost of petroleum in the portfolio;

W_n and E (C_n) are the percentage and expect cost of nuclear fuel in the portfolio;

W_b and E (C_b) are the percentage and expect cost of biomass in the portfolio;

and $W_c + W_{ng} + W_p + W_n + W_b = 1$

Optimization Option: run for 1000 simulations.

Software: Crystal Ball and OptQuest;

Data: Energy Cost (Consumer Price) by Source from Annual Energy Review of EIA;

Solution 1 results from OptQuest:

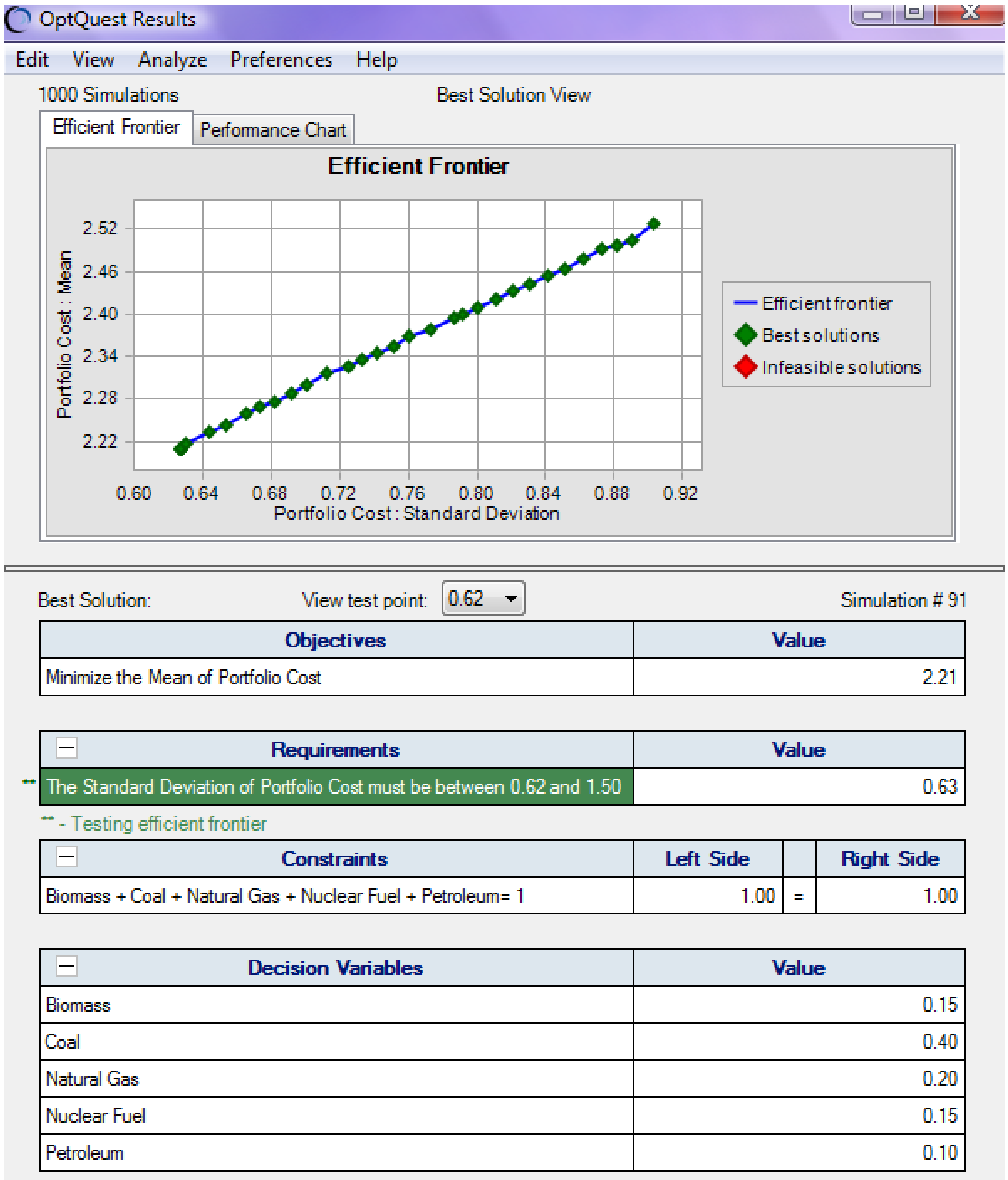


Figure 5-17: OptQuest Simulation Results for Solution 1

Solution 2 results from OptQuest:

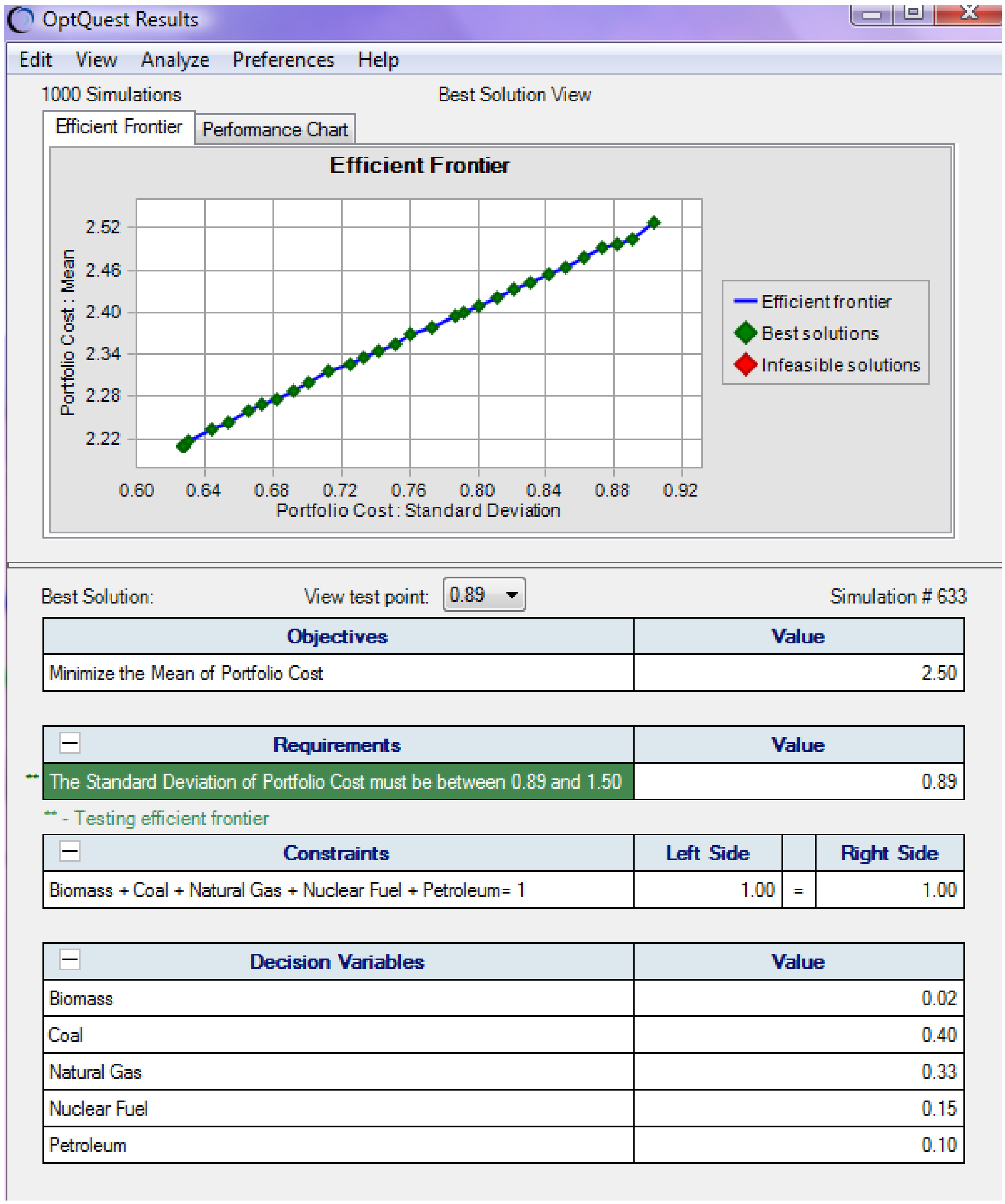


Figure 5-18: OptQuest Simulation Results for Solution 2

	Portfolio Cost	Portfolio Risk/SD	Biomass	Coal	Natural Gas	Nuclear Fuel	Petroleum
Best	$2.21	0.63	15.00%	40.00	20.00%	15.00%	10.00%

Solution 1				%			
Best Solution 2	$2.50	0.89	2.00%	40.00 %	33.00%	15.00%	10.00%
Change (Solution 2 to Solution 1)	-11.6% (percentage)	-29.21% (percentage)	13.00%	0.00%	-13.00%	0.00%	0.00%

Table 5-7: Case Two Results Comparison

Analysis: keeping the consumption of coal, nuclear and petroleum unchanged and increasing the percentage of biomass usage by 13% (from solution 2 to solution 1, Table 5-7), it will reduce natural gas consumption by 13%, which will lower the portfolio cost by 11.6% from $2.50 per million Btu to $2.21 per million Btu with a decreasing of portfolio risk by 29.21% from 0.89 to 0.63.

Result:

1) Without considering the social cost, increasing the usage of natural gas will cause the increase of portfolio cost and its associated risk (Solution 2, Figure 5-18).
2) Without considering the social cost, increasing the usage of biomass will reduce the portfolio cost and its associated risk, especially the usage of biomass (Solution 1, Figure 5-17).
3) Without considering the social cost, biomass is preferable compared to natural gas, and solution 1 is the optimal energy portfolio with a portfolio risk range from 0.5 to 0.9.

5.3 EPM Simulation by Sector

From energy users' perspective, energy is consumed in four different sectors: residential, commercial, industrial and transportation sector. For each sector, there are only several different main energy sources, for example, energy consumption for transportation mainly comes from petroleum, and energy resources used for residential and commercial sectors are petroleum, natural gas and some other energy for electricity. To optimize energy consumption by sector, EPM model needs to find out the optimal combination of energy resources for each sector; however, only industrial sector has been selected for the EPM simulation in the analysis because this sector contains the most energy resources that can offer a better portfolio with wider variety.

5.3.1 EPM Simulation Parameters

Energy Cost

EPM model will simulate based on available data covering the energy cost for industrial sector from 1970 to 2007 for four energy recourse: coal, natural gas, petroleum, and biomass (Appendix 5). Figure 5-19 shows the consumer prices for each energy source, and the prices are used as a proxy of energy cost, because consumer prices are more reasonable to capture the real portfolio cost for energy consumers.

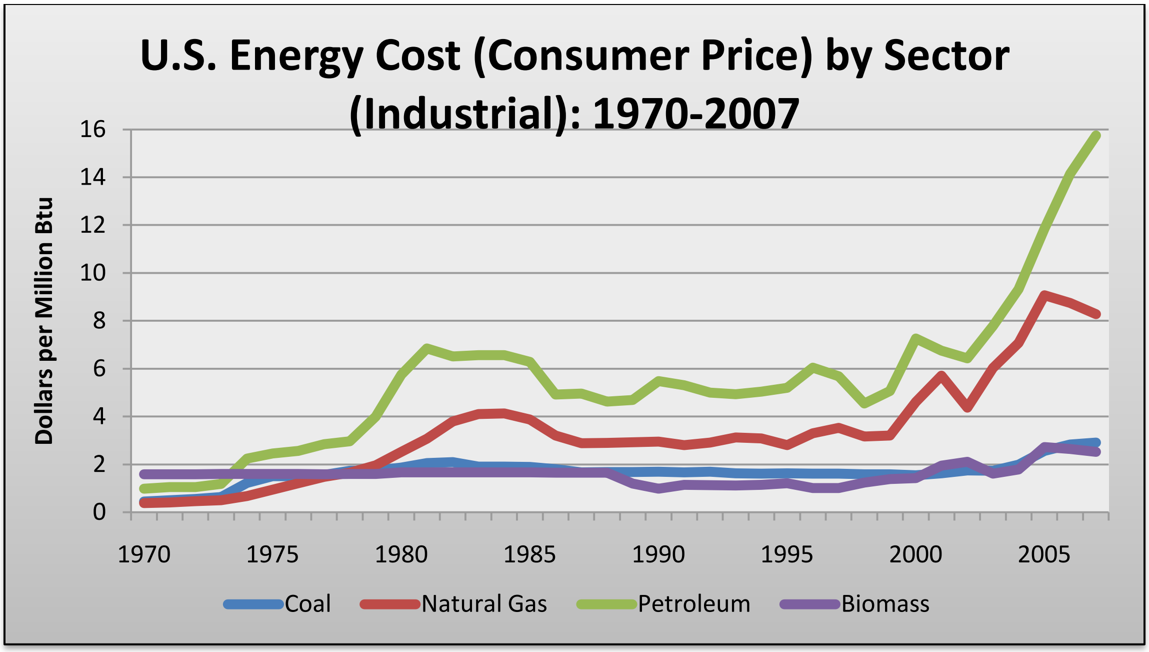


Figure 5-19: U.S. Energy Cost (Consumer Price) by Sector (Industrial): 1970-2007

	Coal_Ind	Natural Gas_Ind	Petroleum_Ind	Biomass_Ind
Mean	1.66	3.36	5.54	1.59
SD	0.52	2.20	3.20	0.41
Min	0.45	0.38	0.98	0.99
Max	2.91	9.07	15.75	2.73

Table 5-8: Energy Cost Statistics for Industrial Sector

Table 5-8 shows some basic statistics from data analysis, and mean and standard deviation will be needed for setting up the distributions for each energy resource. Table 5-9 is the results from Crystal Ball data analysis, and it summarizes the mean of energy costs and their correlations. Energy cost sensitivity analysis is also available in the Appendix 6.

	Coal_Ind	Natural Gas_Ind	Petroleum_Ind	Biomass_Ind
Mean	1.664473684	3.364473684	5.542105263	1.587105263
Correlations:				

Coal_Ind	1.0000	0.6712	0.7522	0.6210
Natural Gas_Ind		1.0000	0.9097	0.4387
Petroleum_Ind			1.0000	0.4766
Biomass_Ind				1.0000

Table 5-9: Energy Cost Correlation from Crystal Ball

Energy Cost Distribution

Before using the OptQuest optimization, the distributions for energy costs are needed. Running data analysis in the Crystal Ball will generate a distribution that fits the sample. Figure 5-20, 5-22, 5-24, and 5-26 illustrate the best fits of distribution for coal, natural gas, petroleum, and biomass are logistic distribution, maximum extreme distribution, logistic distribution, and logistic distribution, respectively.

Data analysis in the Figure 5-20 shows that the probability distribution of coal is continuous with a higher kurtosis (the peakedness of a distribution), therefore the best fit for coal is logistic distribution other than normal distribution. The parameters for logistic distribution are: mean (μ) and scale (s), the mean parameter is the average of a set of values; the scale parameter can be estimated by the formula: $s = \sqrt{\frac{3*variance}{\pi^2}}$. In this case, according to the statistic results of coal, the values for parameters are: μ (mean) = 1.66, s (scale) = 0.28, therefore, the distribution assumption for coal has been defined in the Figure 5-21.

The function of the distribution for coal is:

$$f(x) = \frac{e^{-(\frac{x-\mu}{s})}}{s(1+e^{-(\frac{x-\mu}{s})})^2} = \frac{e^{-(\frac{x-1.66}{0.28})}}{0.28(1+e^{-(\frac{x-1.66}{0.28})})^2}$$

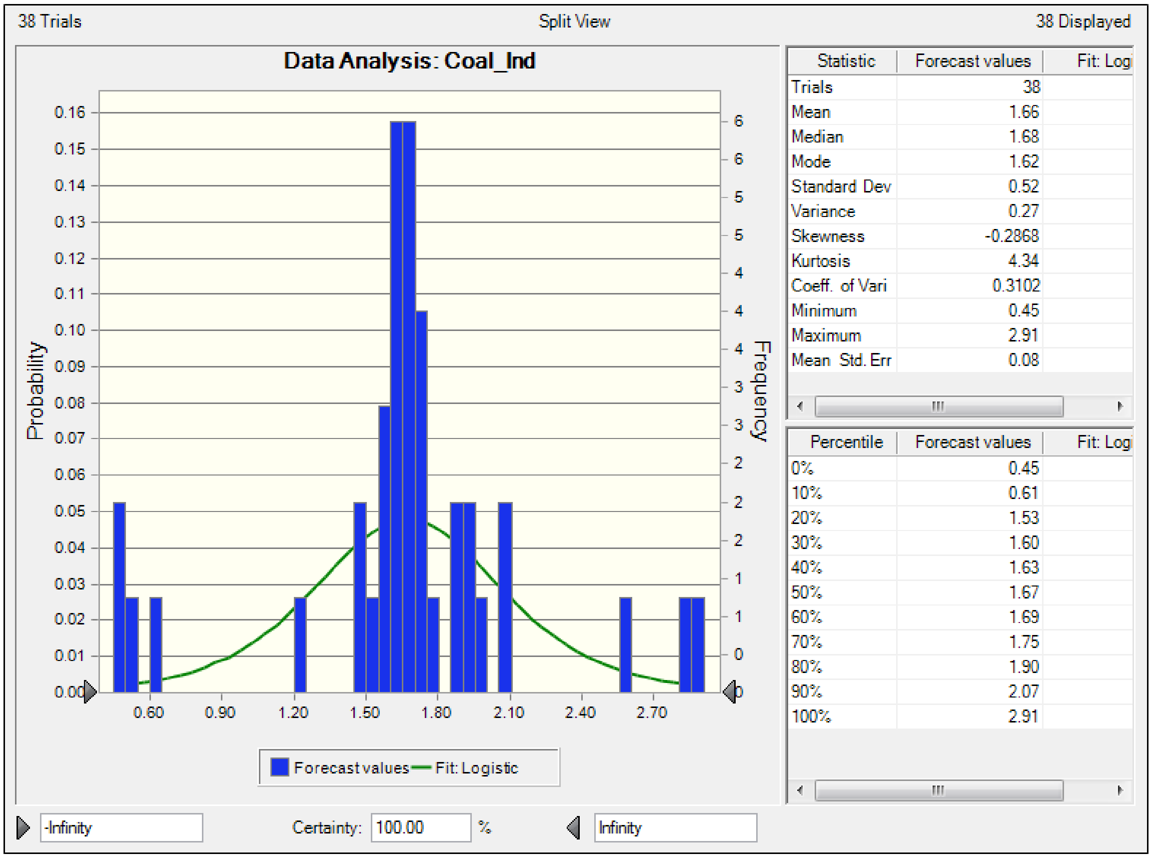


Figure 5-20: Data Analysis for Coal_ Ind

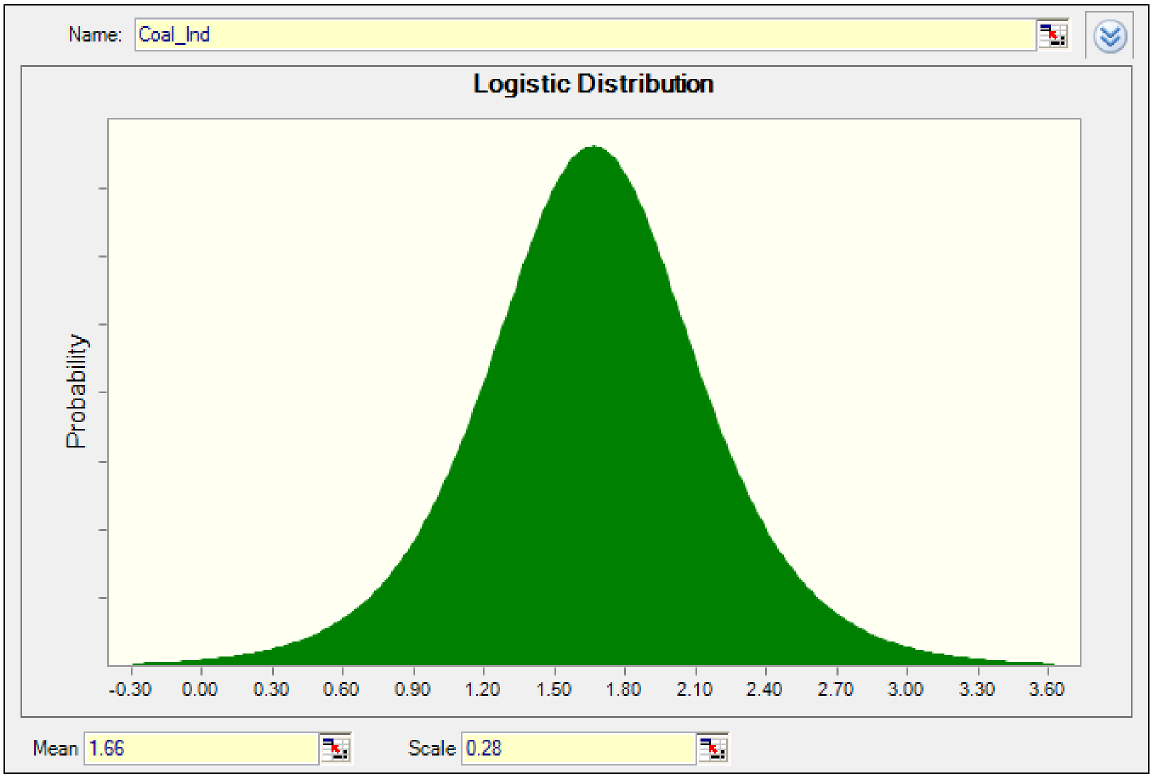


Figure 5-21: Distribution Assumption for Coal_ Ind

Data analysis in the Figure 5-22 shows the probability distribution of natural gas is skewed to the right where most of data are near the minimum rate; therefore the best fit for natural gas is maximum extreme distribution, a positively skewed form of the extreme value distribution. Maximum extreme distribution has two parameters: likeliest (m) and scale (s), the likeliest parameter (m) represents the most likely value for the variable (the highest point on the probability distribution or mode), the scale parameter can be estimated by the formula: $s = \sqrt{\frac{6*variance}{\pi^2}}$. In this case, according to the statistic results of natural gas, the values for parameters are: m (likeliest) = 2.8, s (scale) = 1.72. Therefore, the distribution assumption for natural gas has been defined in the Figure 5-23.

The function of the distribution for natural gas is:

$$f(x) = \frac{1}{s}\left(e^{-\frac{(x-m)}{s}}\right)e^{-e^{-\frac{(x-m)}{s}}} = \frac{1}{1.72}\left(e^{-\frac{(x-2.8)}{1.72}}\right)e^{-e^{-\frac{(x-2.8)}{1.72}}}$$

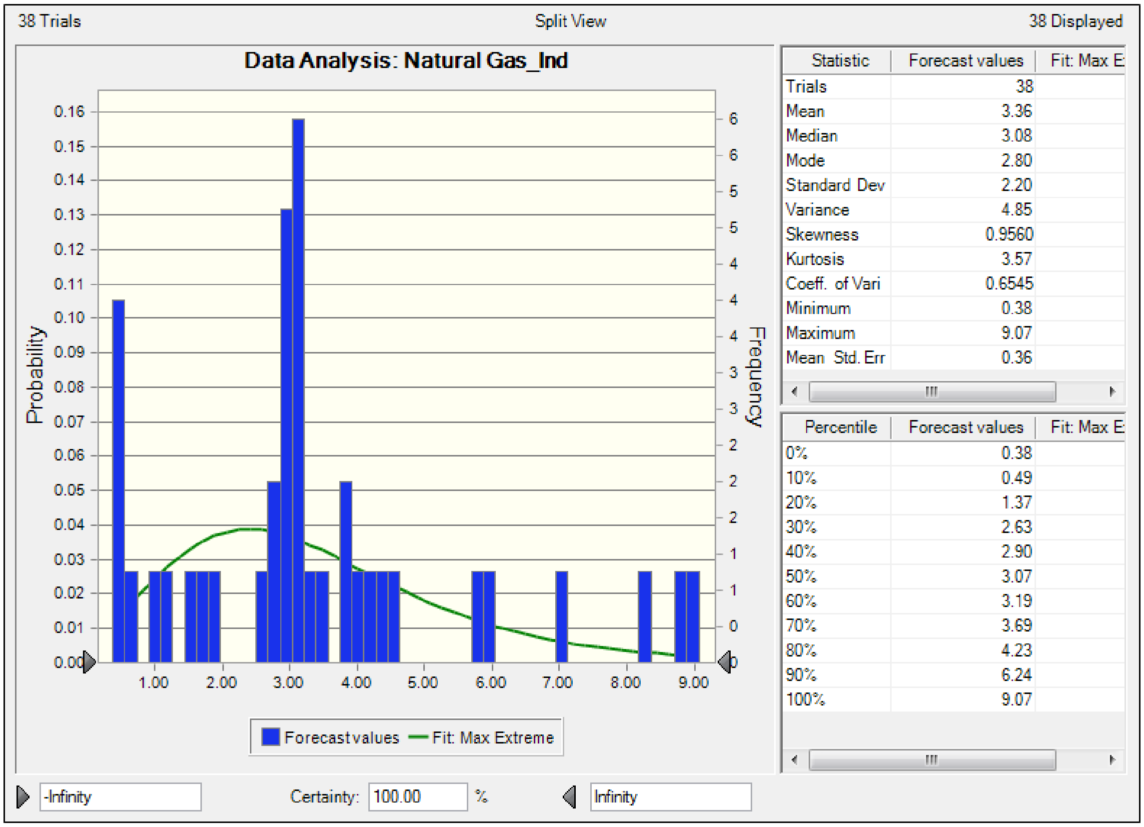


Figure 5-22: Data Analysis for Natural Gas_ Ind

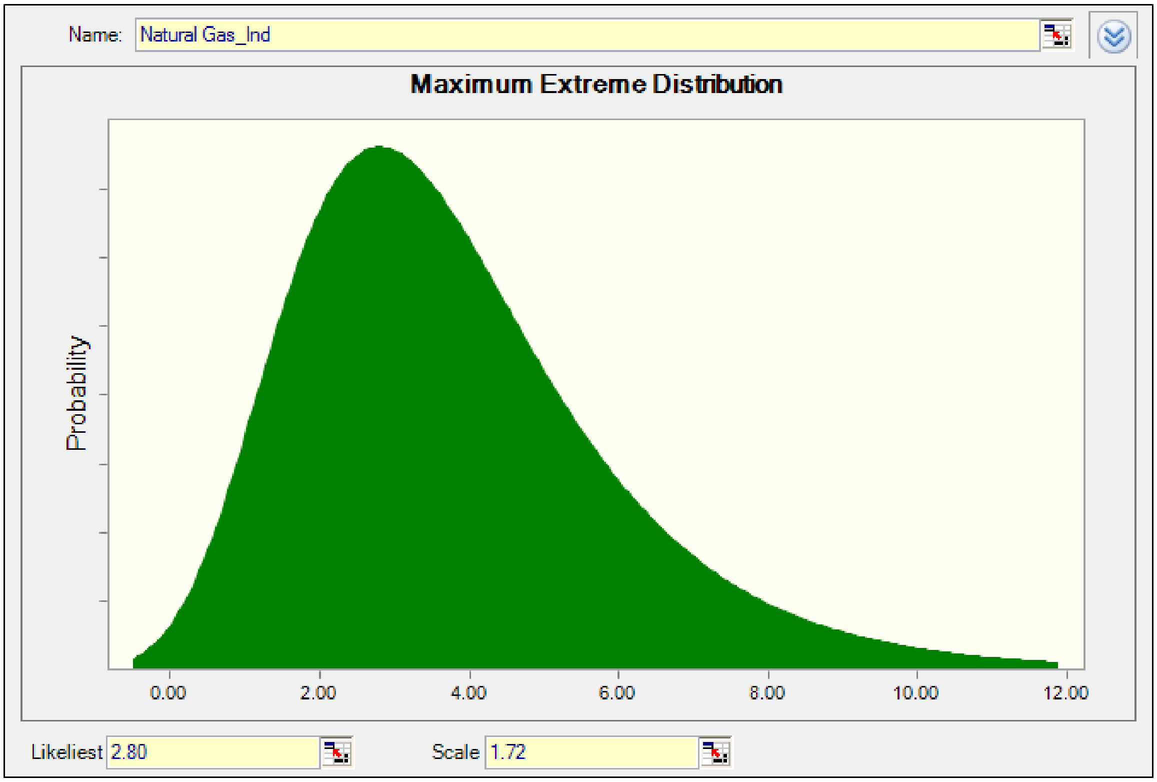


Figure 5-23: Distribution Assumption for Natural Gas_ Ind

Data analysis in the Figure 5-24 shows that the probability distribution of petroleum is continuous shape with a higher kurtosis (the peakedness of a distribution), therefore the best fit for petroleum is logistic distribution other than normal distribution The parameters for logistic distribution are: mean (μ) and scale (s), the mean parameter is the average of a set of values, the scale parameter can be estimated by the formula: $s = \sqrt{\frac{3*variance}{\pi^2}}$. In this case, according to the statistic results of petroleum, the values for parameters are: μ (mean) = 5.54, s (scale) = 1.76, therefore, the distribution assumption for petroleum has been defined in the Figure 5-25.

The function of the distribution for petroleum is:

$$f(x) = \frac{e^{-(\frac{x-\mu}{s})}}{s(1+e^{-(\frac{x-\mu}{s})})^2} = \frac{e^{-(\frac{x-5.54}{1.76})}}{1.76(1+e^{-(\frac{x-5.54}{1.76})})^2}$$

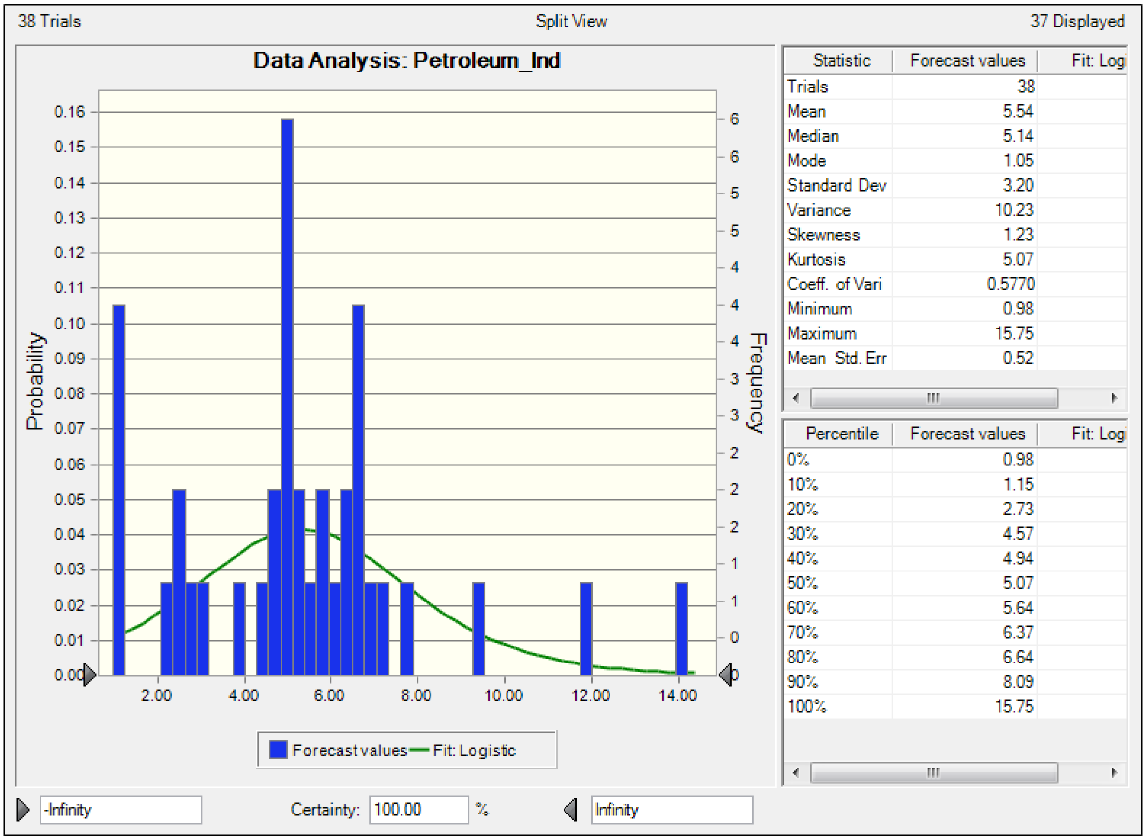


Figure 5-24: Data Analysis for Petroleum_ Ind

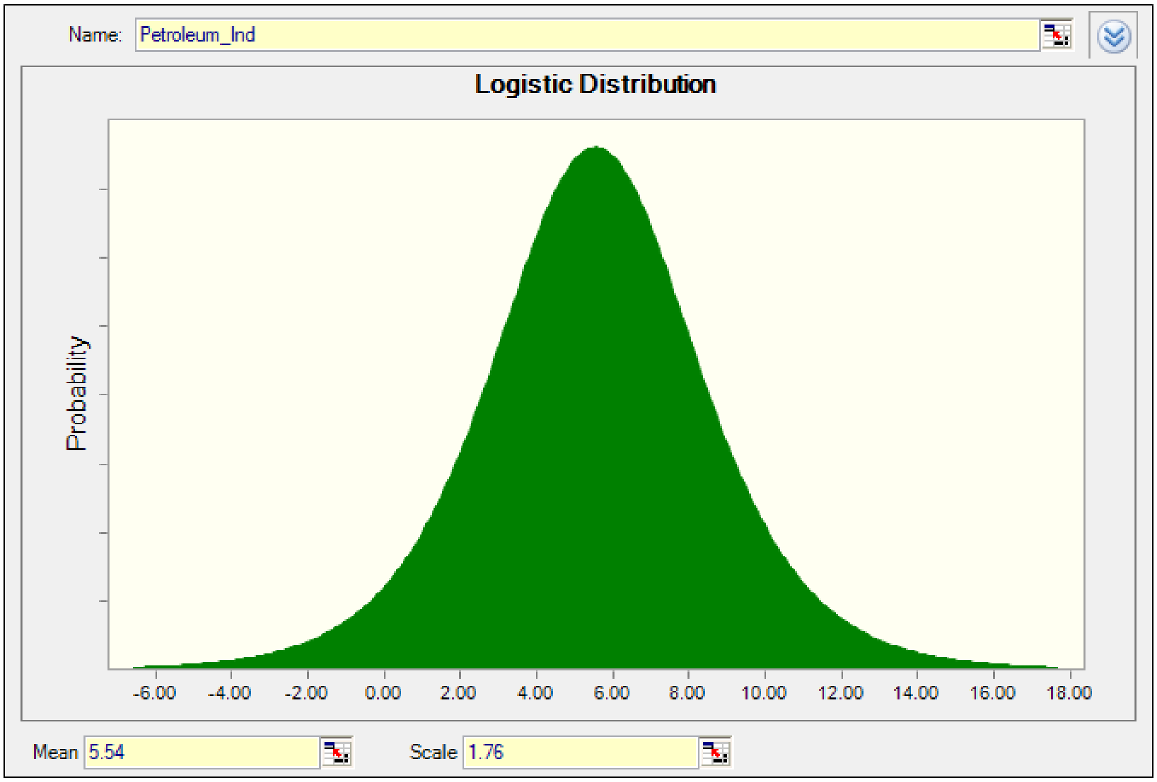


Figure 5-25: Distribution Assumption for Petroleum_ Ind

Data analysis in the Figure 5-26 shows that the probability distribution of biomass is continuous shape with a higher kurtosis (the peakedness of a distribution); therefore the best fit for biomass is logistic distribution other than normal distribution. The parameters for logistic distribution are: mean (μ) and scale (s), the mean parameter is the average of a set of values; the scale parameter can be estimated by the formula: $s = \sqrt{\frac{3*variance}{\pi^2}}$. In this case, according to the statistic results of biomass, the values for parameters are: μ (mean) = 1.59, s (scale) = 0.22, therefore, the distribution assumption for biomass has been defined in the Figure 5-27.

The function of the distribution for biomass is:

$$f(x) = \frac{e^{-(\frac{x-\mu}{s})}}{s(1+e^{-(\frac{x-\mu}{s})})^2} = \frac{e^{-(\frac{x-1.59}{0.22})}}{0.22(1+e^{-(\frac{x-1.59}{0.22})})^2}$$

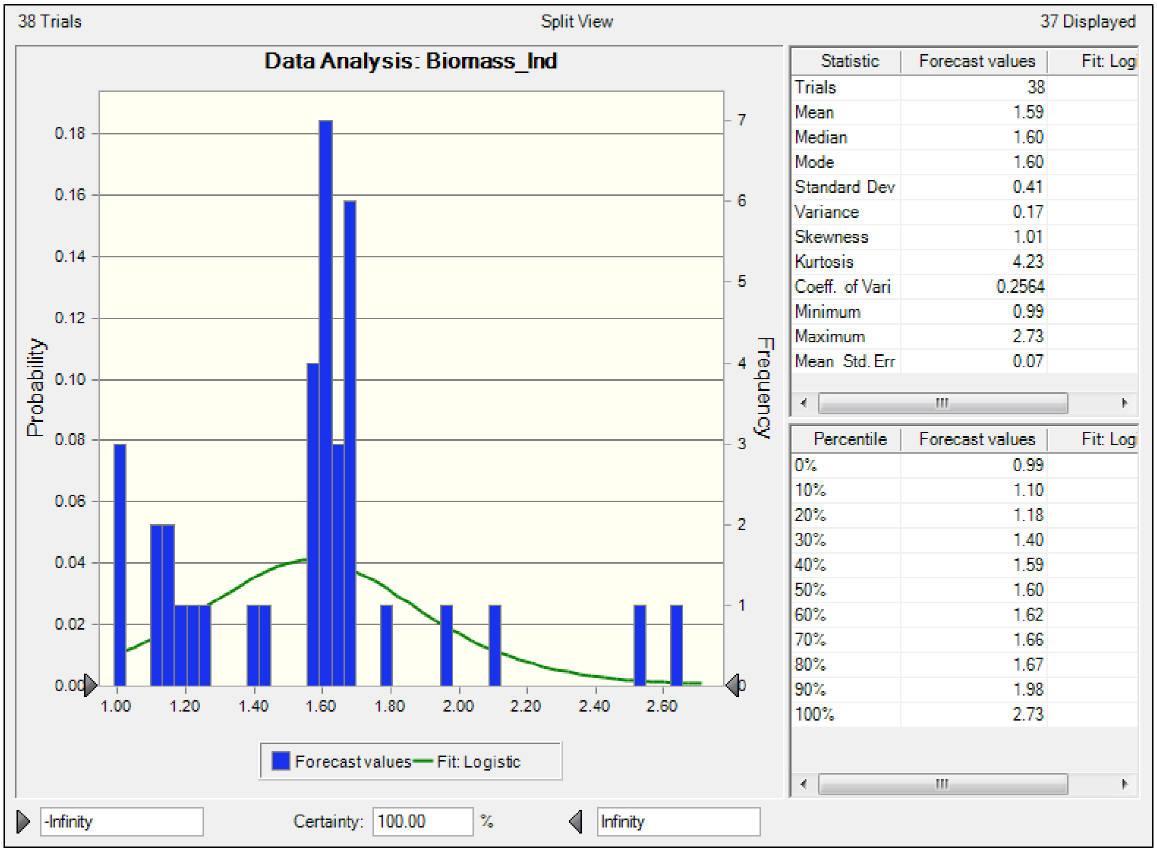


Figure 5-26: Data Analysis for Biomass_ Ind

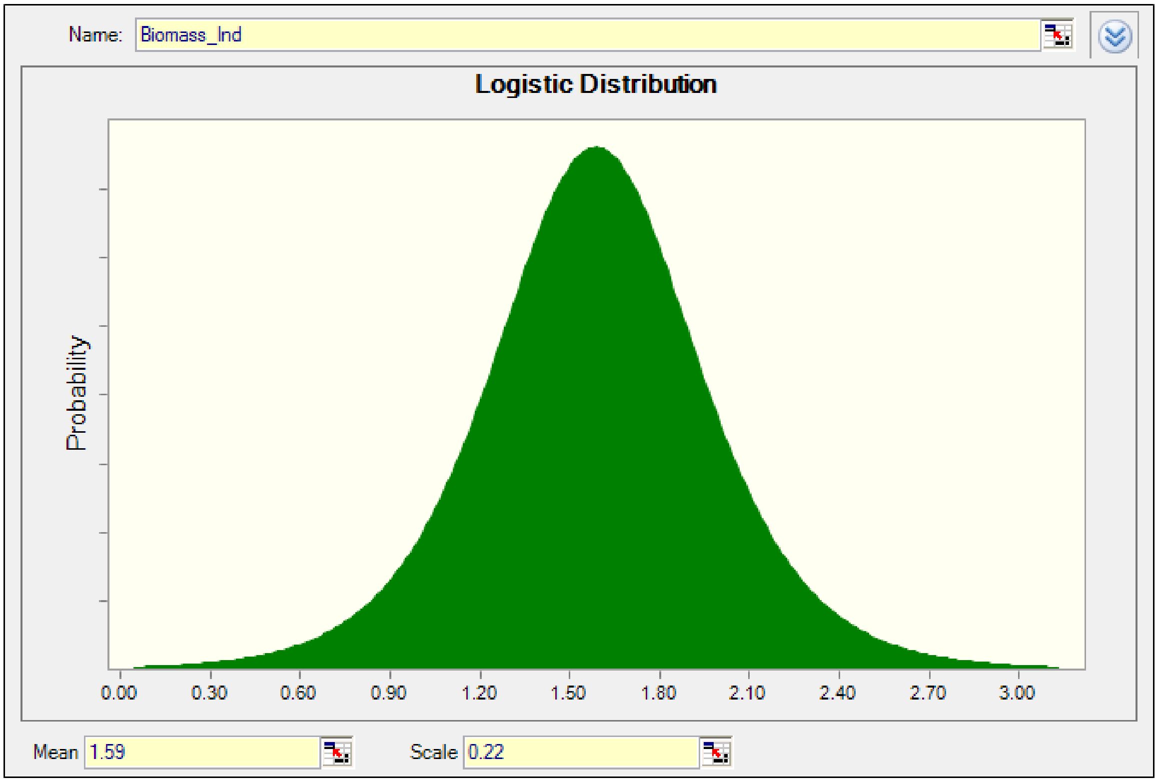


Figure 5-27: Distribution Assumption for Biomass_ Ind

Energy Percentage Bound

Min and Max comes from Energy Information Administration Annual Energy Review "Industrial Sector Energy Consumption, 1949-2009", lower and upper bounds are based on the min and max of consumption percentage. Lower and upper (Table 5-10) are used to set up the bound parameter of each decision variable.

Percentage	Coal	Natural Gas	Petroleum	Biomass
Min	7.57%	25.25%	27.46%	3.66%
Max	43.08%	43.51%	45.49%	10.65%
Lower	5%	20%	20%	3%
Upper	45%	50%	50%	15%

Table 5-10: Energy Consumption (Percentage) Bound by Sector: 1949-2009

5.3.2 Case Analysis

Objectives: Minimize the mean of Portfolio Cost_Ind

Requirement: the standard deviation of Portfolio Cost_Ind must be between 0.5 and 1.5

Efficient Frontier: vary the lower bound from 0.5 to 0.9 in steps of 0.01.

Decision Variables (Table 5-11, Figure 5-28):

Decision Variable	Lower Bound	Base Case	Upper Bound	Type
Biomass_Ind	0.03	0.03	0.15	Continuous
Coal_Ind	0.05	0.05	0.45	Continuous
Natural Gas_Ind	0.20	0.20	0.50	Continuous
Petroleum_Ind	0.20	0.20	0.50	Continuous

Table 5-11: Decision Variable Bounds for EPM by Sector

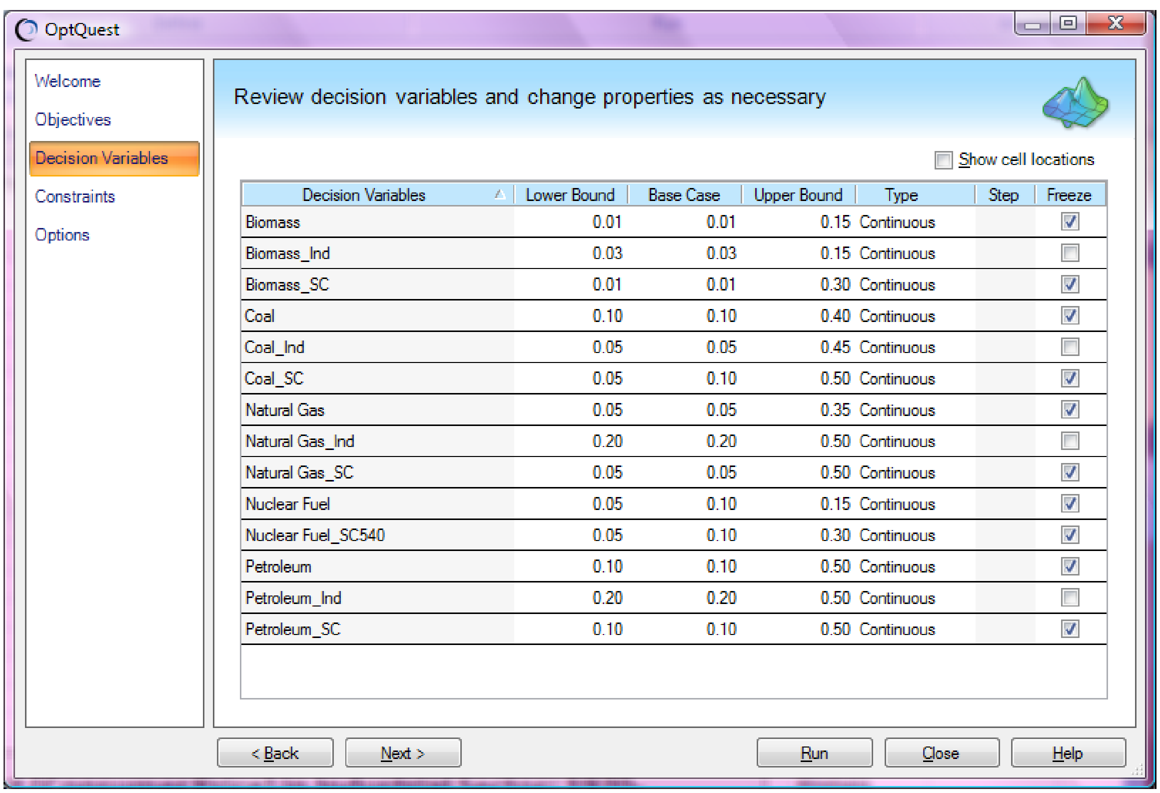


Figure 5-28: Decision Variable Bounds for EPM by Sector in the Crystal Ball OptQuest

Constraints: Biomass_Ind + Coal_Ind + Natural Gas_Ind + Petroleum_Ind = 1

The expected portfolio cost formula:

$$E(C_p) = W_c E(C_c) + W_{ng} E(C_{ng}) + W_p E(C_p) + W_b E(C_b)$$

Where:

$E(C_p)$ is their expected energy portfolio costs (Dollars per Million Btu).

W_c and $E(C_c)$ are the percentage and expect cost of coal in the portfolio,

W_{ng} and $E(C_{ng})$ are the percentage and expect cost of natural gas in the portfolio;

W_p and $E(C_p)$ are the percentage and expect cost of petroleum in the portfolio;

W_b and $E(C_b)$ are the percentage and expect cost of biomass in the portfolio;

and $W_c + W_{ng} + W_p + W_b = 1$

Optimization Option: run for 500 simulations;

Software: Crystal Ball and OptQuest;

Data: Energy Cost (Consumer Price) by Sector (Industrial) from Annual Energy Review of EIA.

Best Solution 1 from OptQuest: Optimal portfolio with the 0.79 level of portfolio risk

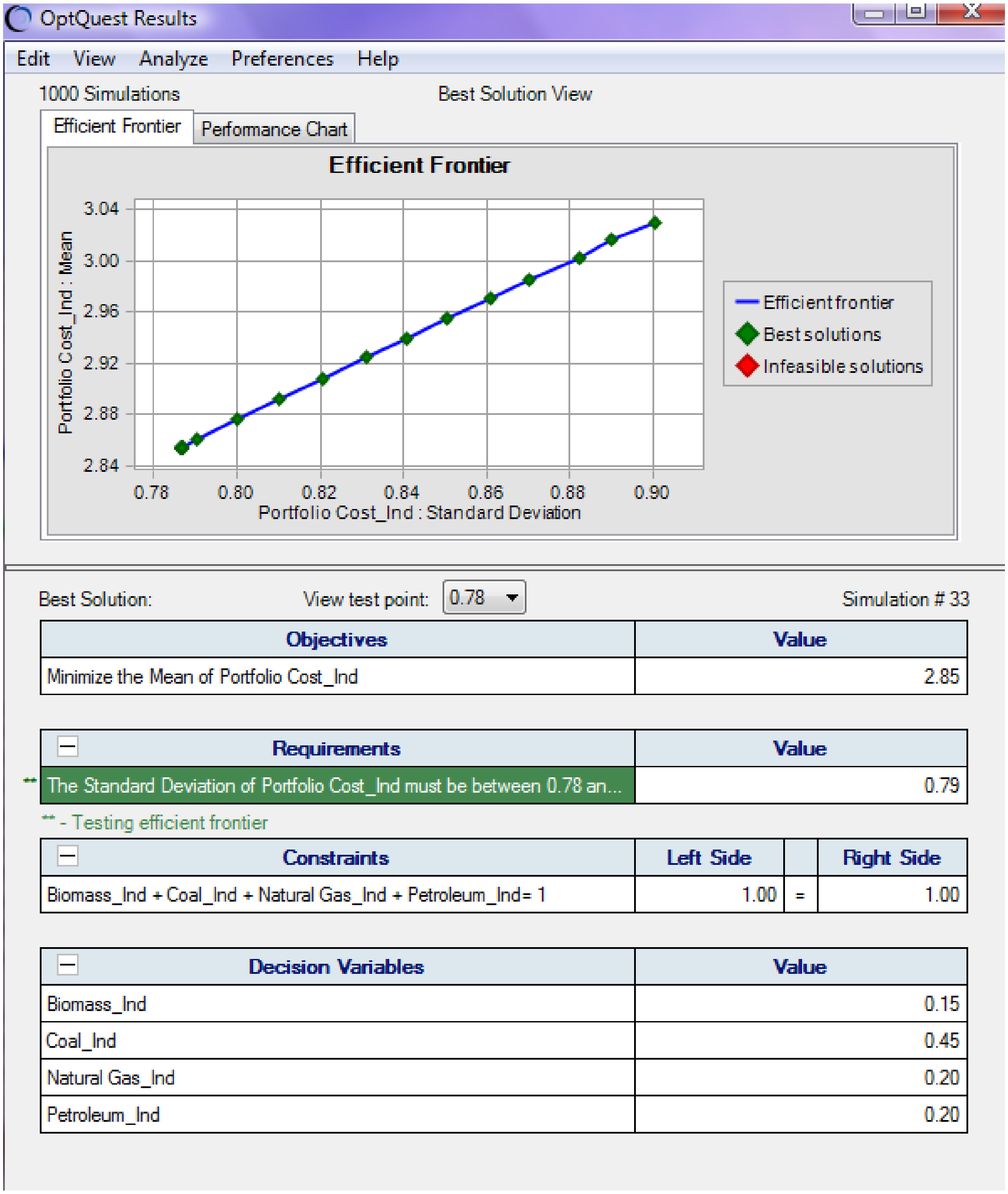


Figure 5-29: OptQuest Simulation Results for Solution 1

Best Solution 2 from OptQuest: Optimal portfolio with the 0.9 level of portfolio risk

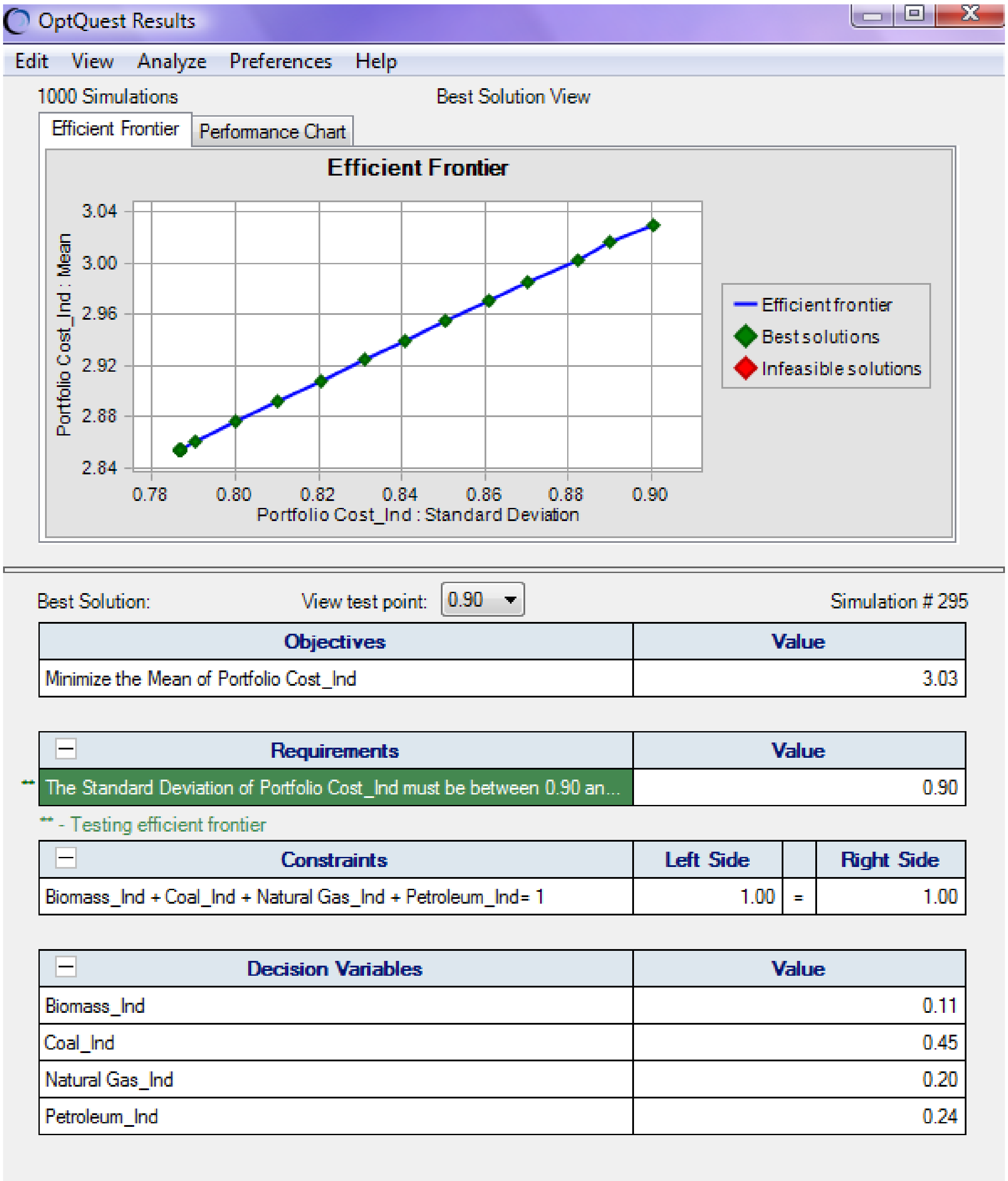


Figure 5-30: OptQuest Simulation Results for Solution 2

	Portfolio Cost	Portfolio Risk/SD	Biomass	Coal	Natural Gas	Petroleum
Best Solution 1	$2.85	0.79	15.00%	45.00%	20.00%	20.00%

Best Solution 2	$3.03	0.9	11.00%	45.00%	20.00%	24.00%
Change (Solution2 to Solution1)	-5.94% (Percentage)	-12.22% (Percentage)	4.00%	0.00%	0.00%	-4.00%

Table 5-12: Simulation Results Comparison

Analysis: keeping the consumption of coal and natural gas unchanged and increasing the percentage of biomass usage by 4% (from solution 2 to solution 1, Table 5-12), it will reduce petroleum consumption by 4%, which will lower the portfolio cost by 5.94% from $3.03 per million Btu to $2.85 per million Btu with a decreasing of portfolio risk by 12.22% from 0.9 to 0.79.

Result:

1) Although the prices of petroleum, natural gas and coal for industrial sector are relatively lower than the prices by source, portfolio cost ($2.85/million Btu) by sector (industrial) is still much higher than portfolio cost by source ($2.21/million Btu in Case 2 and $1.78/million Btu in Case 1). It is only because nuclear fuel, a relatively cheaper resource, is not included in the industrial consumption.
2) Without considering the social cost, increasing the usage of petroleum will cause the increase of portfolio cost and its associated risk (Solution 2, Figure 5-30).
3) Without considering the social cost, increasing the usage of biomass will reduce the portfolio cost and its associated risk (Solution 1, Figure 5-29).
4) Without considering the social cost, biomass is preferable than petroleum, and solution 1 is the optimal energy portfolio with a portfolio risk range from 0.5 to 0.9.

Chapter 6 EPM Simulation with Social Cost

According to the results from EPM simulation in the Chapter 5, petroleum is a relatively more expensive and risky resource compared to other resources, solution with less petroleum has lower cost with less risk; therefore, natural gas, coal, nuclear fuel and biomass become alternative options to reduce the portfolio cost of energy consumption. However, this analysis is only based on private cost from fuels, doesn't include the social cost, and the portfolio combination may change as the increase of energy cost due to social cost. This chapter will explain how the portfolio will change due to the social cost of energy resources.

The impacts from burning energy resources on the environment and the society are considered as the social cost, and should be added as part of energy costs, but the amount of social cost is hard to determine due to the inexplicitness of social cost. Therefore, the social cost in this chapter is estimated as the percentage of energy private cost, and simulated by different scenarios with certain percentage. And the EPM simulation scenarios only considers the social cost impacts from coal, natural gas and nuclear, the social cost simulation for petroleum isn't included because petroleum is already not an optimal option in the energy consumption due to high and volatile prices

6.1 Social Cost of Coal

Coal is a very cheap energy compared to petroleum, natural gas and biomass (Figure 5-1) considering only energy private cost. From the perspective of private cost, coal should be the major resources in the energy consumption because of its low price. The first scenario "Coal_ SC" shows that coal has about 50 percent (the upper bound or maximum) in the optimal energy portfolio without the social cost. However, coal produces most of carbon dioxide, even more than petroleum and natural gas per million Btu (Table 4-1), the social cost of coal from the environment should be included into the energy cost.

Remaining the costs of natural gas, petroleum, nuclear fuel and biomass unchanged, the simulation will only consider the social cost of coal, and analyze how the combination of optimal portfolio will change as the increase of social cost of coal. The EPM model simulation will be based on the same group of data as the EPM simulation by source in Chapter 5, and the same distribution assumptions for coal, natural gas, petroleum, nuclear fuel and biomass (Table 6-1).

Coal: Min Extreme		**Natural Gas:** Logistic		**Petroleum:** Logistic		**Nuclear:** Beta		**Biomass:** Gamma	
Likeliest	1.27	Mean	4.06	Mean	6.20	Min	0.18	Location	1.15
Scale	0.29	Scale	1.33	Scale	1.87	Max	0.73	Shape	2
						Alpha	3.00	Scale	0.3
						Beta	2.00		

Table 6-1: Distribution Assumption for Energy Resources

The EPM model has run ten scenarios, and each scenario simulates 1000 simulations with a certain percentage change of social cost. Table 6-2 shows the comparison of scenario simulations results, for each scenario simulation only the optimal portfolio with lowest portfolio cost and least risk has been selected for comparison (refer to Appendix 7 for coal scenario simulation).

Scenarios Simulation Results with Social Cost of Coal

Scenarios	Portfolio Cost	Portfolio Risk /SD	Biomass_ SC	Coal _ SC	Natural Gas_SC	Nuclear _ SC	Petroleum _ SC
Coal_ SC	$1.74	0.5	2%	50%	5%	30%	13%
Coal_SC10	$1.78	0.5	2%	50%	5%	30%	13%
Coal_SC30	$1.87	0.5	3%	50%	5%	30%	12%
Coal_SC50	$1.94	0.5	4%	50%	5%	30%	11%
Coal_SC70	$2.01	0.5	5%	50%	5%	30%	10%
Coal_SC100	$2.15	0.53	8%	47%	5%	30%	10%
Coal_SC110	$2.21	0.54	8%	47%	5%	30%	10%
Coal_SC120	$2.21	0.51	23%	31%	5%	30%	11%
Coal_SC150	$2.29	0.5	30%	18%	12%	30%	10%
Coal_SC300	$2.53	0.7	30%	5%	25%	30%	10%

Table 6-2: Scenario Simulation Comparison for Coal

Results:

1) Without considering the social cost of coal (Coal_ SC scenario), the consumption of coal in the optimal portfolio should be 50%, at the maximum.
2) The percentage of coal in the optimal energy portfolio doesn't change from no social cost (Coal_ SC) included to 70% social costs (Coal_ SC 70 scenario).
3) The consumption of coal starts to decrease when social cost increase to 100%, and keeps decreasing as the increase of social cost, and portfolios switch to favor biomass.
4) When the social cost rises to 300%, the consumption of coal will drop to 5% (the minimum), and the optimal portfolio switch to more consumption from biomass and natural gas.

Analysis:

In Table 6-2, from no social cost (Scenario Coal_ SC) to 70% social cost (Coal_SC70), the portfolio combinations of energy resources have no changes, which indicates the coal prices with no more than 70% social cost would have no impact on the combination for the optimal energy portfolio. This could be explained as the competitive cost advantage of coal, because the price of coal is relatively cheap than petroleum, natural gas and biomass. Therefore, within a certain range of social cost increase, the price of coal including social cost doesn't have significant impact on the combination of optimal energy portfolio.

However, with the increase of social cost to 100%, the portfolio mix starts to change (Coal_SC100 scenario, Figure 6-1), and the consumption of coal drops by 3% with a switch to biomass. As the increasing of social cost to 120% (Scenario Coal_SC120, Figure 6-2), the percentage of coal usage reduces a significant amount, to 31%, which means the consumption of coal will have a significant decrease once the social cost increase to 120% or more, and it will reduce to the minimum, only 5%, and switch to favor biomass and natural gas if the social cost is 3 times (300%) than the private cost of coal (Scenario Coal_SC300, Figure 6-3). Figure 6-1, 6-2 and 6-3 are the results from the Coal_SC100 scenario, Coal_SC120 scenario, and Coal_SC300 scenario simulations, and illustrate the changes of energy portfolio with the impacts from the social cost of coal. The results demonstrate that the consumption of coal starts to lose the cost competitive advantage once the social cost increase to 100% or more and switch to biomass at first and then natural gas, as the increasing of social cost the whole energy portfolio will change due to too high social cost of coal.

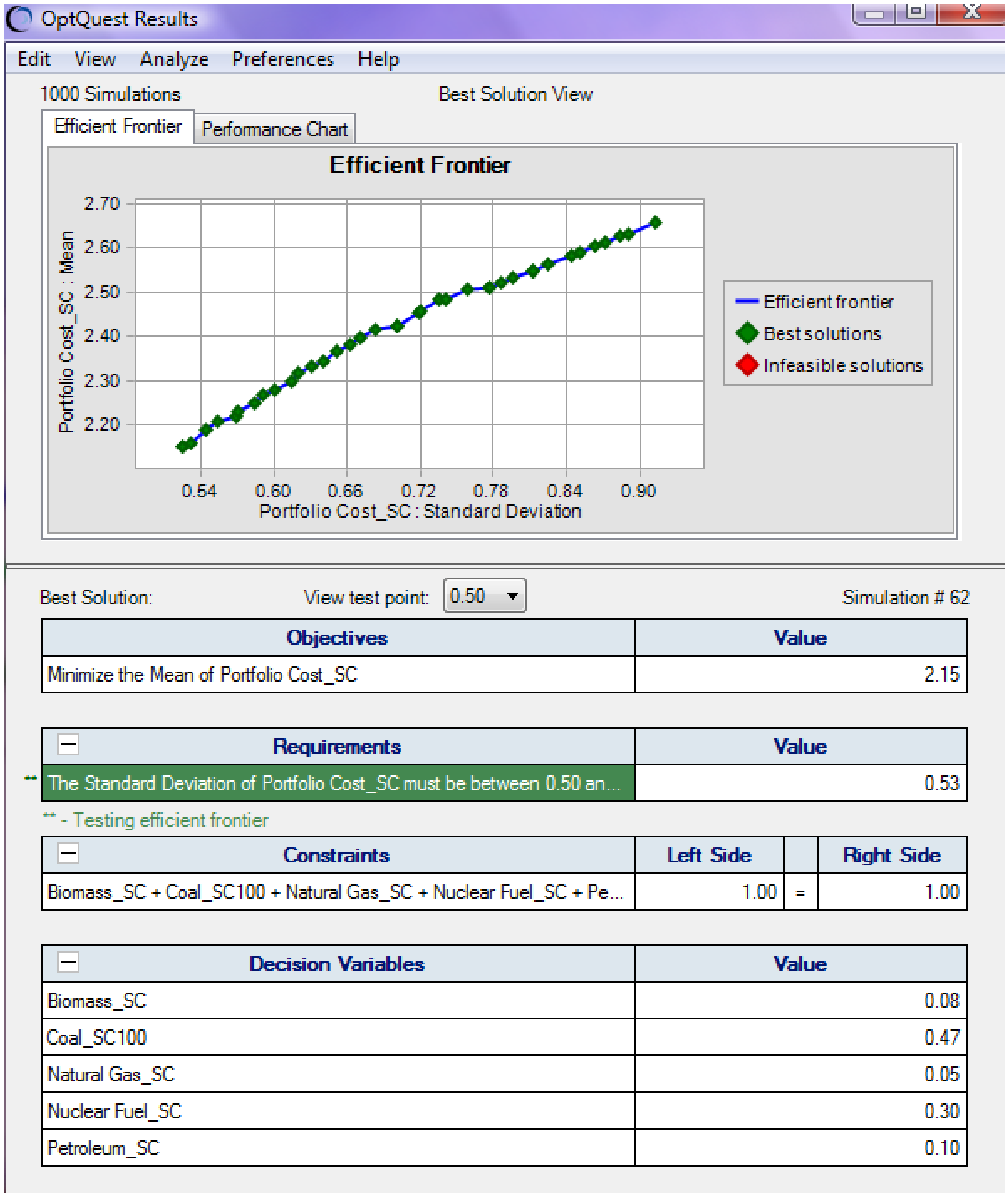


Figure 6-1: Scenario Simulation Result with 100% Social Cost

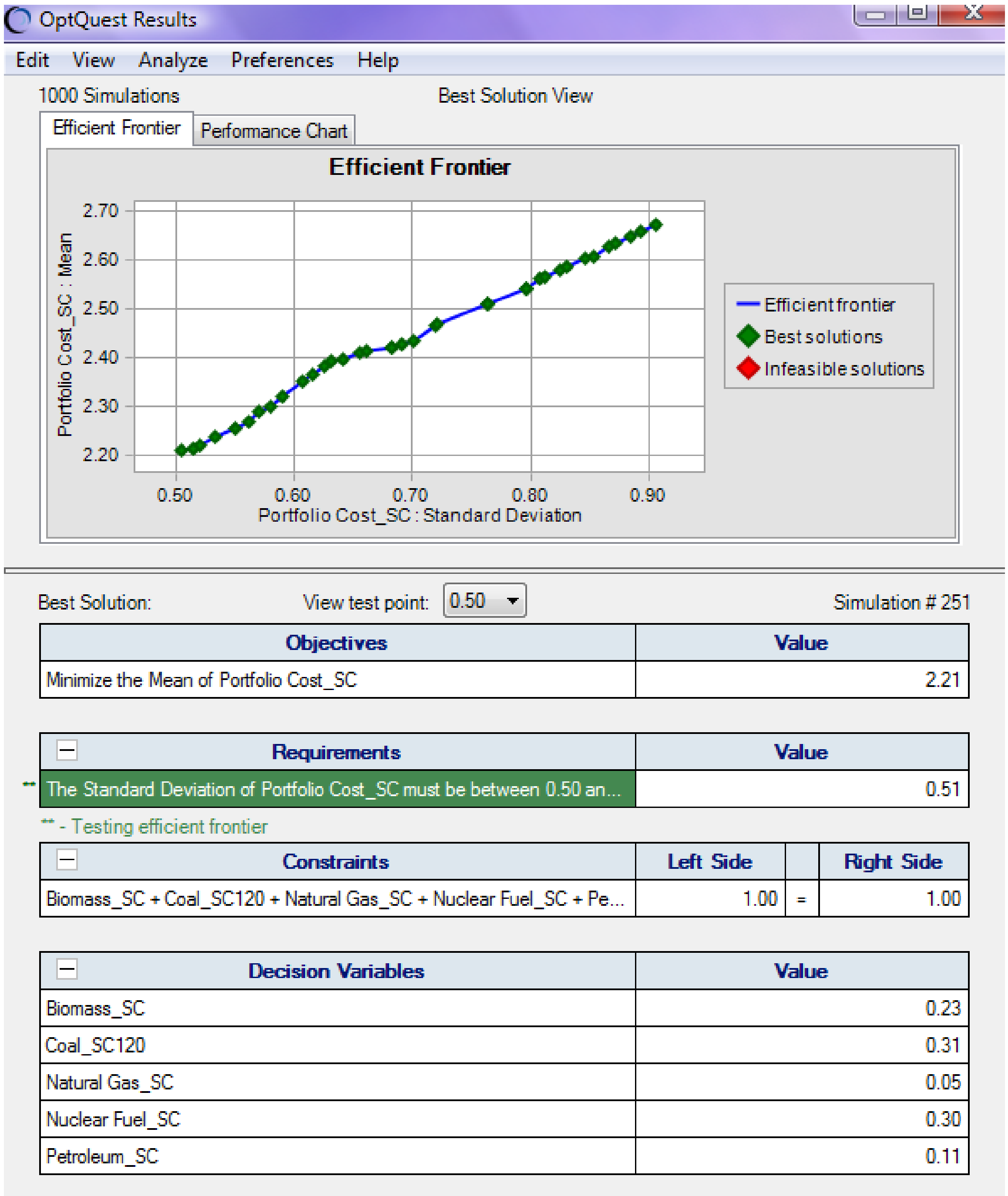


Figure 6-2: Scenario Simulation Result with 120% Social Cost

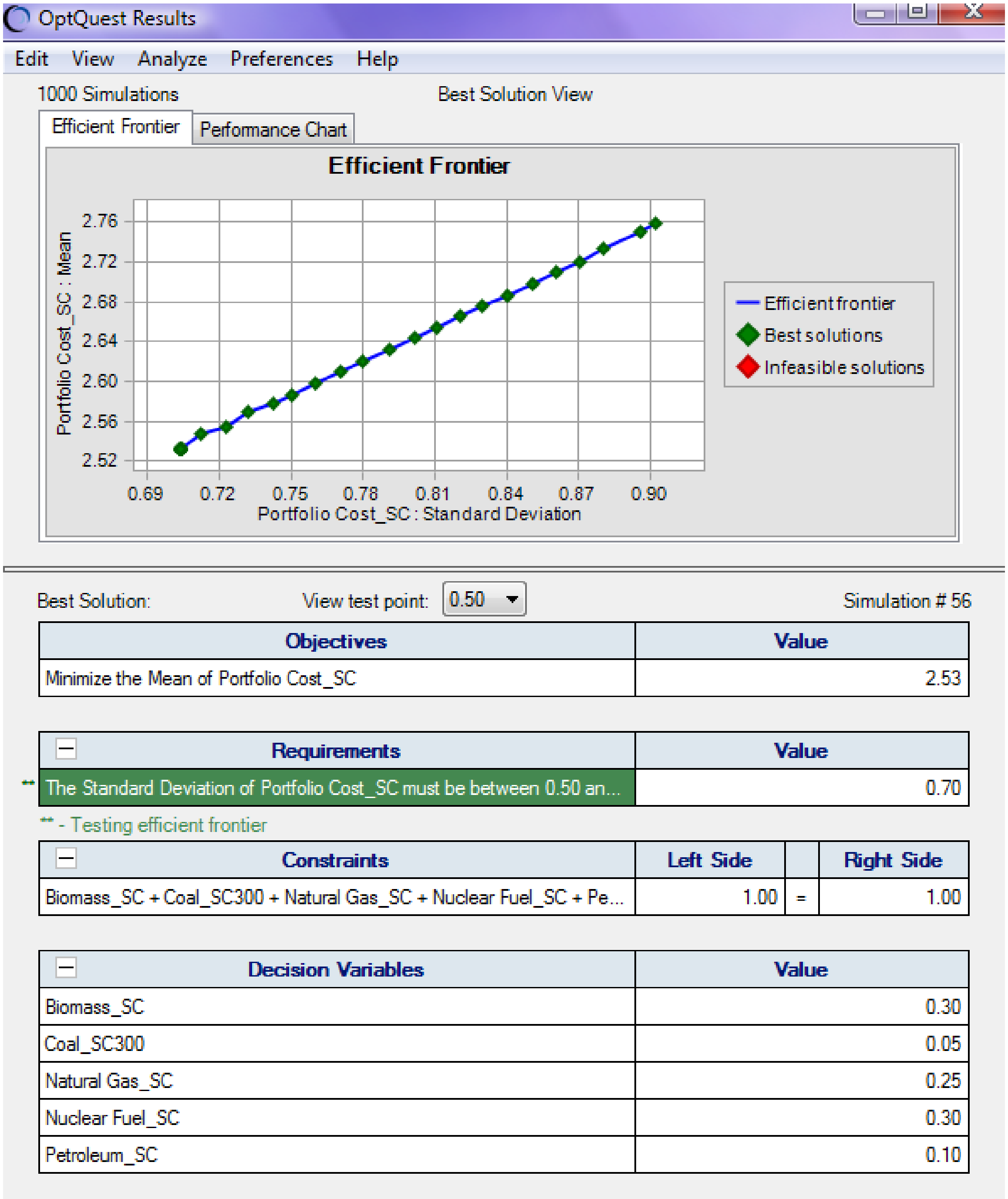


Figure 6-3: Scenario Simulation Result with 300% Social Cost

6.2 Social Cost of Natural Gas

Natural gas is a relative cheap energy compared to petroleum (Figure 5-1) considering only the energy private cost, and it has about 5 percent in the optimal energy portfolio without the social cost, such as scenario "Natural Gas_ SC" (Table 6-3). Although natural gas is considered to be clean compared to coal and petroleum, the environmental impacts from burning natural gas are still a big issue, and the social cost for natural gas should be considered and included into the EPM simulation.

Keeping the costs of coal, petroleum, nuclear fuel and biomass unchanged, the simulation will only consider the social cost of natural gas, and analyze how the combination of portfolio will changes as the increase of social cost. The EPM model simulation will be based on the same group of data as the EPM simulation by source in Chapter 5, and the same distribution assumptions for coal, natural gas, petroleum, nuclear fuel and biomass (Table 6-1). The EPM model has run five scenarios, and each scenario simulates 1000 simulations with a certain percentage change of social cost. Table 6-3 shows the comparison of scenario simulations with certain percentages of social cost, for each scenario simulation only the optimal portfolio with lowest portfolio cost and least risk has been selected for comparison (refer to Appendix 8 for natural gas scenario simulation)

Scenarios Simulation Results with Social Cost of Natural Gas							
Scenarios	**Portfolio Cost**	**Portfolio Risk/SD**	**Biomass _SC**	**Coal _SC**	**Natural Gas _SC**	**Nuclear _SC**	**Petroleum _SC**
NG_SC	$1.74	0.5	2%	50%	5%	30%	13%
NG_SC10	$1.77	0.51	2%	50%	5%	30%	13%
NG_SC50	$1.85	0.52	2%	50%	5%	30%	13%

NG_SC100	$1.89	0.5	4%	50%	5%	30%	11%
NG_SC150	$1.96	0.5	7%	50%	5%	28%	10%

Table 6-3: Scenario Simulation Comparison for Natural Gas

Results:

1) The percentage of natural gas consumption in the optimal energy portfolio doesn't change from no social cost (NG_ SC scenario) included to 150% social costs (NG_ SC 150 scenario).

2) The consumption of natural gas always keeps at the lower bound value (minimum) in the optimal portfolio.

Analysis:

The first scenario (NG_SC) without social cost of natural gas shows that the percentage of natural gas in the optimal portfolio with lowest portfolio risk is 5 percent, Table 6-3 shows that the percentage of natural gas consumption in five scenario simulation, from no social cost (Coal_ SC Scenario) to 150% social cost Scenario (Coal_SC150 Scenario), doesn't change any amount, and keeps constant at 5 percent. This result implies that the price of natural gas with social cost almost have no impact on the optimal portfolio combination. This could be explained by the high price of natural gas and the features of efficient frontier optimization.

Natural gas, as the second expensive energy resource after petroleum, will be consumed limited due to its relative high price from cost perspective. By applying the efficient frontier optimization, the optimal energy portfolio will simulate the energy combination with an objective of minimizing the portfolio cost. Basically it will combine only small amount of expensive resources, but large amount of cheap energy. Under these circumstances, natural gas, with a lower bound of 5% and upper bound of 50% (Figure 6-4), will be simulated from 5% (minimum) in order to lower the portfolio cost. Therefore, the result from NG_SC scenario simulation, natural gas accounts only for 5% in the portfolio.

As the increase of natural gas cost due to the addition of social cost, the scenario simulations don't show any change with the energy consumption of natural gas. If the consumption of natural gas doesn't change in the scenario of NG_SC 100 with 100% social cost, it won't change as any more increase of social cost, because the cost of natural gas in the scenario of NG_SC 100 has already exceeded the cost of petroleum. The more expensive of natural gas will only decrease the consumption of natural gas; therefore, the consumption of natural gas should keep at the minimum due to high private cost in the optimal energy portfolio unless the social cost of other resources cause the switch to natural gas, such as coal.

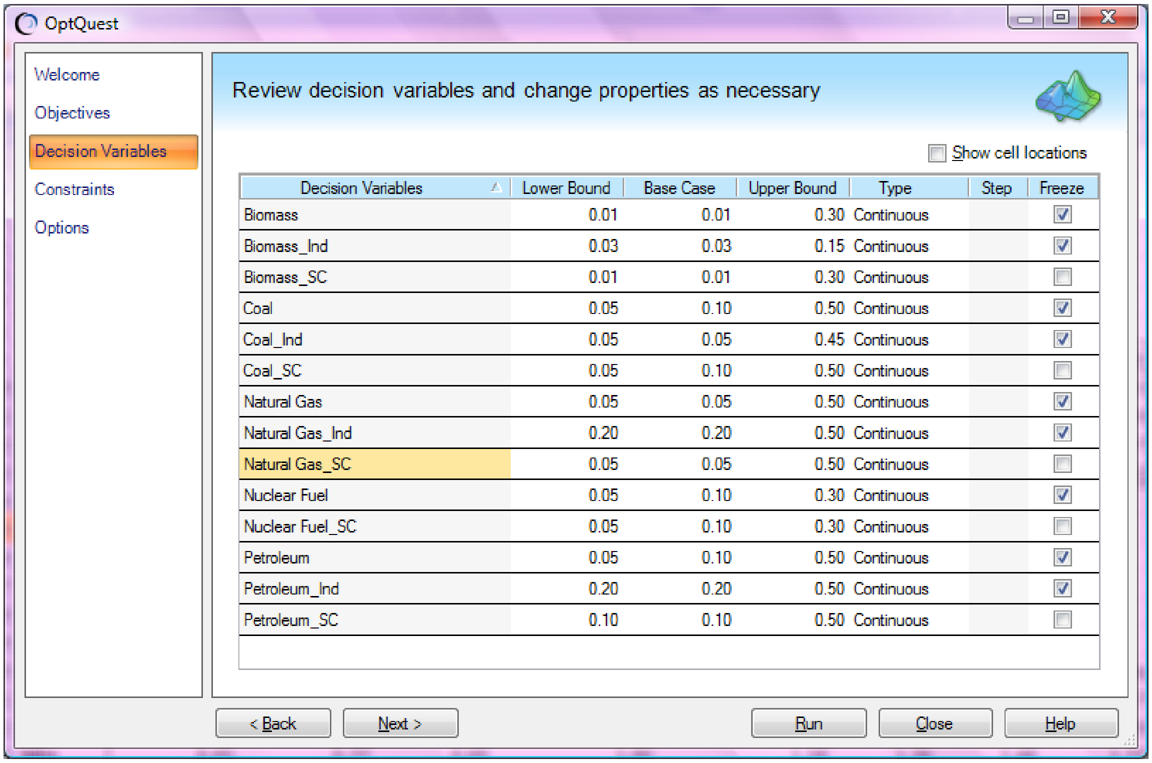


Figure 6-4: Decision Variable for Scenario NG_SC

6.3 Social Cost of Nuclear

Nuclear is the cheapest energy, compared to petroleum, natural gas, coal and biomass (Figure 5-1) considering only the energy private cost. Without the social cost, nuclear will hold a big part in the energy portfolio, just like the scenario "Nuclear_ SC" (Table 6-4), nuclear has about 30% (the upper bound or maximum) in the optimal energy portfolio. However, nuclear energy has severe safety and security problems (Table 4-1), and the impacts of nuclear energy on the human health and society are not negligible. Therefore, the social cost of nuclear should be included as part of energy cost in the EPM simulation.

Keeping the costs of coal, natural gas, petroleum and biomass constant, the simulation will only consider the social cost of nuclear fuel, and analyze how the combination of portfolio will change with the increase of social cost. The EPM model simulation will be based on the same group of data as the EPM simulation by source in Chapter 5, and the same distribution assumptions for coal, natural gas, petroleum, nuclear fuel and biomass (Table 6-1). The EPM model has run 11 scenarios, and each scenario simulates 1000 simulations with a certain percentage change of social cost. Table 6-4 shows the comparison of scenario simulations with certain percentages of social cost, for each scenario simulation only the optimal portfolio with lowest portfolio cost and least risk has been selected for comparison (refer to Appendix 9 for nuclear scenario simulation)

Scenarios Simulation Results with Social Cost of Nuclear							
Scenarios	**Portfolio Cost**	**Portfolio Risk/SD**	**Biomass _SC**	**Coal _SC**	**Natural Gas _SC**	**Nuclear _SC**	**Petroleum _SC**
Nuclear_ SC	$1.74	0.5	2%	50%	5%	30%	13%
Nuclear_ SC50	$1.82	0.51	2%	50%	5%	30%	13%
Nuclear_ SC100	$1.90	0.5	2%	50%	5%	30%	13%
Nuclear_ SC150	$1.98	0.5	2%	50%	5%	30%	13%
Nuclear_ SC200	$2.05	0.51	2%	50%	5%	30%	13%
Nuclear_ SC250	$2.13	0.51	2%	50%	5%	30%	13%
Nuclear_ SC300	$2.20	0.5	3%	50%	5%	29%	13%
Nuclear_ SC350	$2.25	0.5	8%	50%	5%	24%	13%
Nuclear_ SC400	$2.33	0.57	15%	50%	5%	15%	15%
Nuclear_ SC450	$2.35	0.53	12%	50%	15%	13%	10%
Nuclear_ 500	$2.24	0.55	26%	50%	5%	5%	14%

Table 6-4: Scenario Simulation Comparison for Nuclear

Results:

1) Without considering the social cost of nuclear (Scenario "Nuclear_ SC"), the consumption of nuclear should be 30%, at the maximum.

2) The percentage of nuclear in the optimal energy portfolio doesn't change from no social cost (Scenario "Nuclear_ SC") included to 250% social costs (Scenario "Nuclear_ SC 250").
3) The consumption of nuclear starts to decrease when social cost of nuclear increase to 300%, and keeps decreasing as the increase of social cost, and optimal portfolios switch to favor biomass.
4) When the social cost of nuclear rises to 500%, the consumption of nuclear will drop to the minimum, at 5%, and the optimal portfolio switch to more consumption from biomass and a little from petroleum.

Analysis:

In Table 6-4, from no social cost (Nuclear_ SC Scenario) to 250% social cost (Nuclear_SC250 Scenario), the portfolio combinations of energy resources have no changes and nuclear keeps at 30%, the maximal consumption. This indicates the nuclear with no more than 250% social cost would have no impact on the combination of the optimal energy portfolio because of its competitive cost advantage. Nuclear is the cheapest energy resource among petroleum, coal, natural gas and biomass, will be used at the maximum if it keeps at a low cost. Therefore, within a certain range of social cost, the price of nuclear including social cost doesn't have significant impact on the combination of optimal energy portfolio, and nuclear will be still an optimal choice.

However, once social cost increases to 300% (three times than its private cost) in the scenario of Nuclear_SC300 (Figure 6-5), the portfolio mix starts to change with declining usage of nuclear energy. As the increasing of social cost, the percentage of nuclear usage reduces a significant amount, for example, only 15% in the optimal portfolio if social cost rises to 400% (social cost is four times than private cost), and drops to 5% when social cost increase to 500%. This illustrates that if the social cost of nuclear is too high, and reaches 400% or more than the private cost, the consumption of nuclear will have a significant decrease, and drop to the minimal percentage in the optimal portfolio which means the competitive advantage of nuclear will no longer exist. Therefore, this results show that if the social cost of nuclear is within certain range (less than 250%), the consumption of nuclear should be still at the maximum; however it will drop as the extra increase of social cost and reach the minimum with 500% social cost, and biomass and petroleum become more attractive than nuclear.

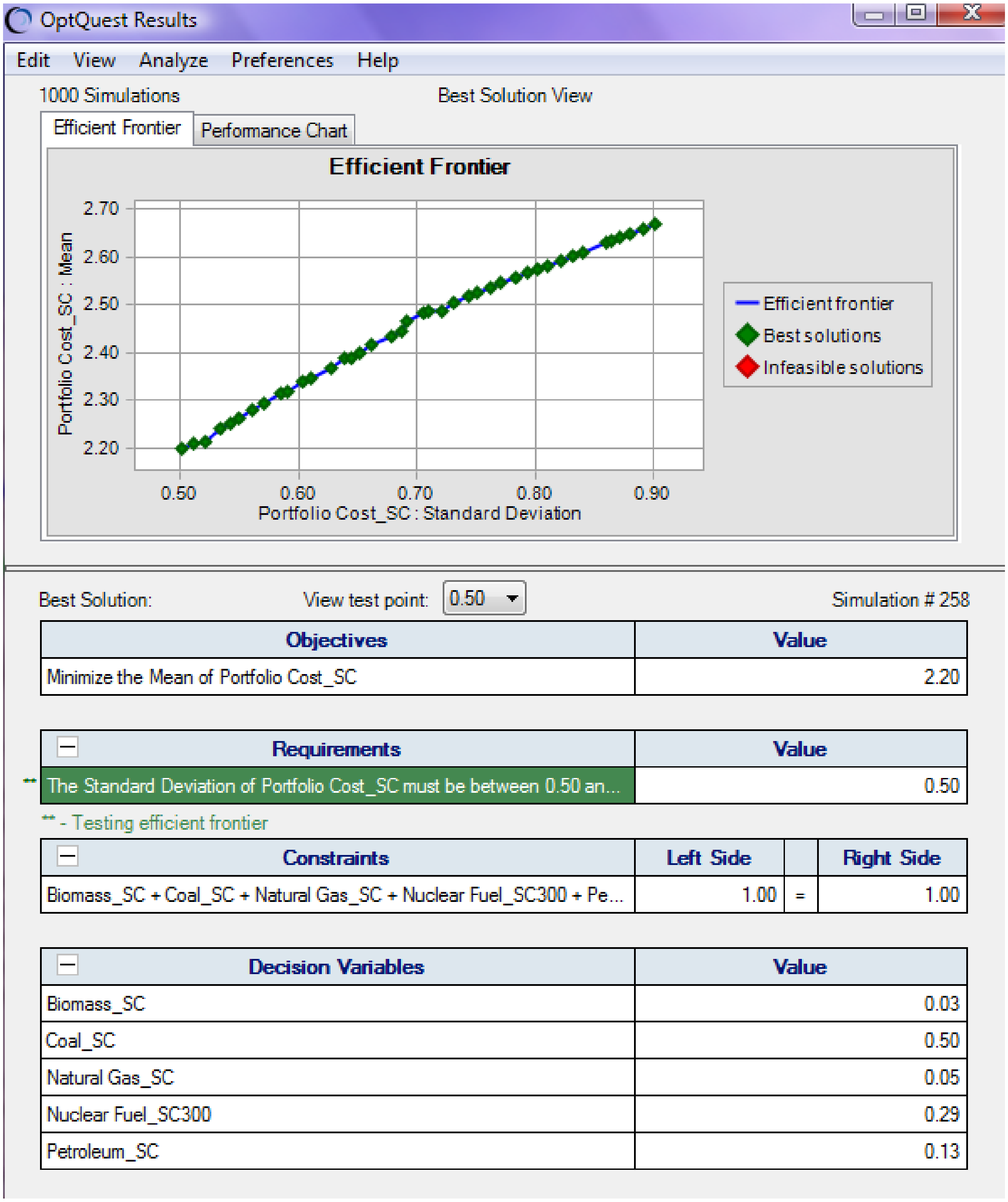


Figure 6-5: Scenario Simulation Result with 300% Social Cost

6.4 Social Cost Discussion

According to previous EPM simulations of social cost of coal, natural gas and nuclear, results show energy consumption structure (optimal energy portfolio) changes with the increase of social cost: with a low level of the social costs, energy portfolio seems remain unchanged, only when the social cost of energy reaches to a certain amount, energy portfolio starts to changes and favors energy resources with lower total cost. Table 6-5 summarizes the breakdown points of social cost from social cost of simulations in section 6.1, 6.2 and 6.3, and the shift of energy portfolio structure due to the increase of social cost of energy resources.

	Coal	**Natural gas**	**Nuclear**
SC Breakdown_1	100% or $1.88/million Btu (2007 price)	N/A	300% or $1.38/million Btu (2007 price)
Portfolio Shift	Biomass	At the minimum unless switch needed	Biomass
SC Breakdown_2	150% or $2.82/million Btu (2007 price)	N/A	400% or $1.84/million Btu (2007 price)
Portfolio Shift	Biomass and Natural gas(small amount)	At the minimum unless switch needed	Biomass and Petroleum(small amount)
SC Breakdown_3	300% or $5.64/million Btu (2007 price)	N/A	500% or $2.3/million Btu (2007 price)
Portfolio Shift	Biomass and Natural gas(small amount)	At the minimum unless switch needed	Biomass and Petroleum(small amount)

Table 6-5: Social Cost Breakdowns and Portfolio Shifts[1]

Based on the EPM social cost estimates in Table 4-4, the current levels of social-private cost can be calculated using the EPM social cost divided by the current private cost, shown in Table 6-6. The percentage of social-private cost indicates the impacts of energy consumption on the environment and society and energy choices for the optimal energy portfolio, for example, with high level of social cost, the simulation shows that the optimal portfolio will prefer biomass and natural gas rather than coal since the social cost of coal is more than 300% of its private cost.

	Petroleum	Coal	Natural gas	Nuclear
EPM Social Cost(SC)_Low ($/Million Btu)	$0.37	$0.48	$0.27	N/A
EPM Social Cost(SC)_Central ($/Million Btu)	$1.57	$2.00	$1.11	N/A
EPM Social Cost(SC)_High ($/Million Btu)	$4.85	$6.20	$3.45	N/A
Private Cost(PC)_2007($/Million Btu)	$16.7	$1.88	$9.3	$0.46
SC/PC_ Low (percentage)	2%	25%	3%	200%*
SC/PC_ Central (percentage)	9%	107%	12%	350%*
SC/PC_ High (percentage)	29%	**330%**	37%	500%*

Table 6-6: Social-Private Cost (Percentage) Estimates (2007)[2]

Comparing the social-private cost estimates in Table 6-6 with social cost breakdowns (Table 6-5), it seems that the optimal energy portfolio in 2007 with low and central level

[1] Breakdown points are estimated by the EPM social cost simulation with only one social cost involved at one time, keeping other energy unchanged with no social cost included.
[2] * SC/PC percentages are estimated according to the social cost breakdowns in Table 6-5 except SC/PC of nuclear, SC/PC of nuclear is supposed based on the social cost simulation in section of 6.3, because the EPM social cost of nuclear is unknown from U.S. IWG report.

of social cost, coal should be favored, but will switch to biomass at high level of social cost. In order to test the validity of breakdown points estimates for social costs, and the overall impacts of social costs on the optimal portfolio, this dissertation also simulate the EPM model with all types of social costs included simultaneously. Using the social-private cost estimates in 2007 (Table 6-6), EPM simulations are run at three levels: low level of social cost (Figure 6-6), central level of social cost (Figure 6-7) and high level of social cost (Figure 6-8).

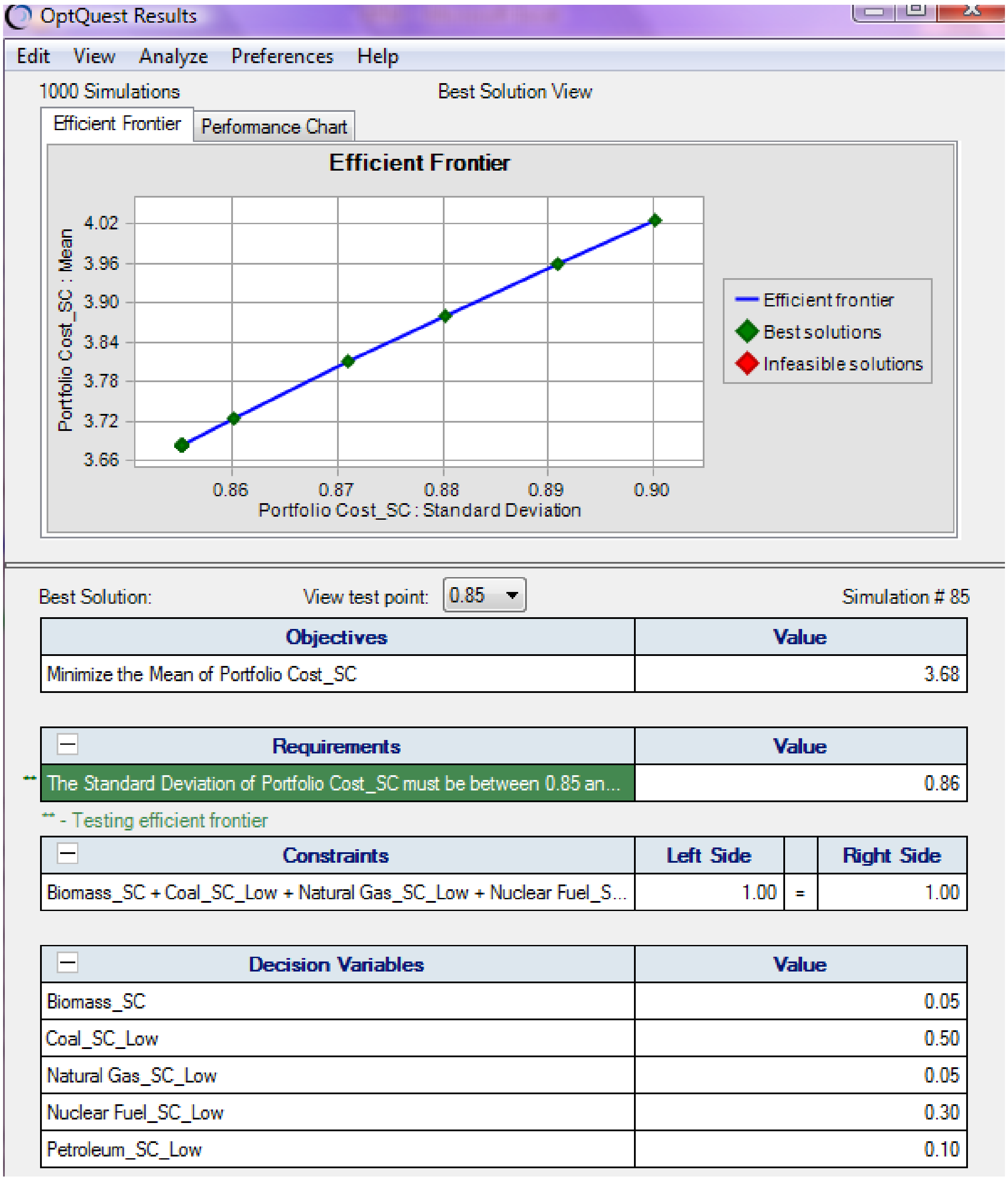


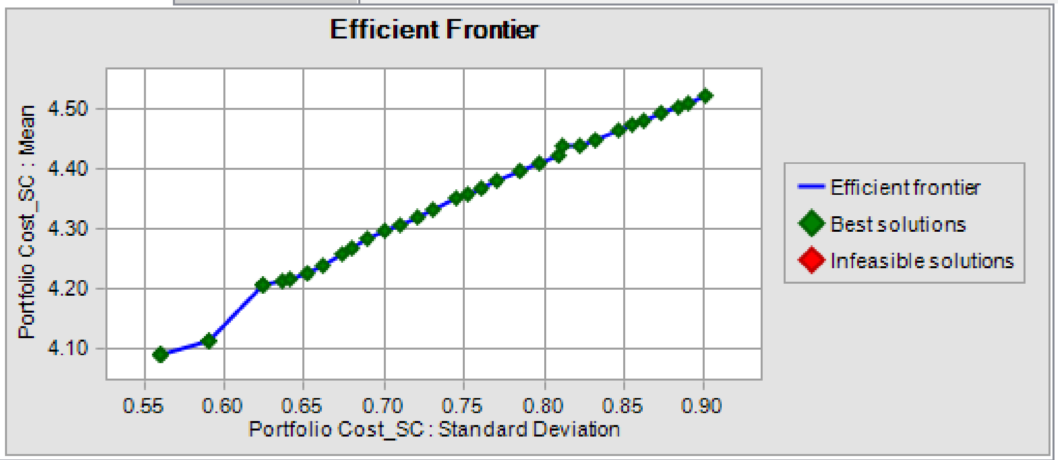
Figure 6-6: EPM simulation result at low level of social cost

OptQuest Results

Edit View Analyze Preferences Help

1000 Simulations — Best Solution View

Efficient Frontier | Performance Chart



Best Solution: View test point: 0.56 Simulation # 208

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	4.09

Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.56 an...	0.56

** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC_Central + Natural Gas_SC_Central + Nuclear F...	1.00	=	1.00

Decision Variables	Value
Biomass_SC	0.05
Coal_SC_Central	0.50
Natural Gas_SC_Central	0.05
Nuclear Fuel_SC_Central	0.30
Petroleum_SC_Central	0.10

Figure 6-7: EPM simulation result at central level of social cost

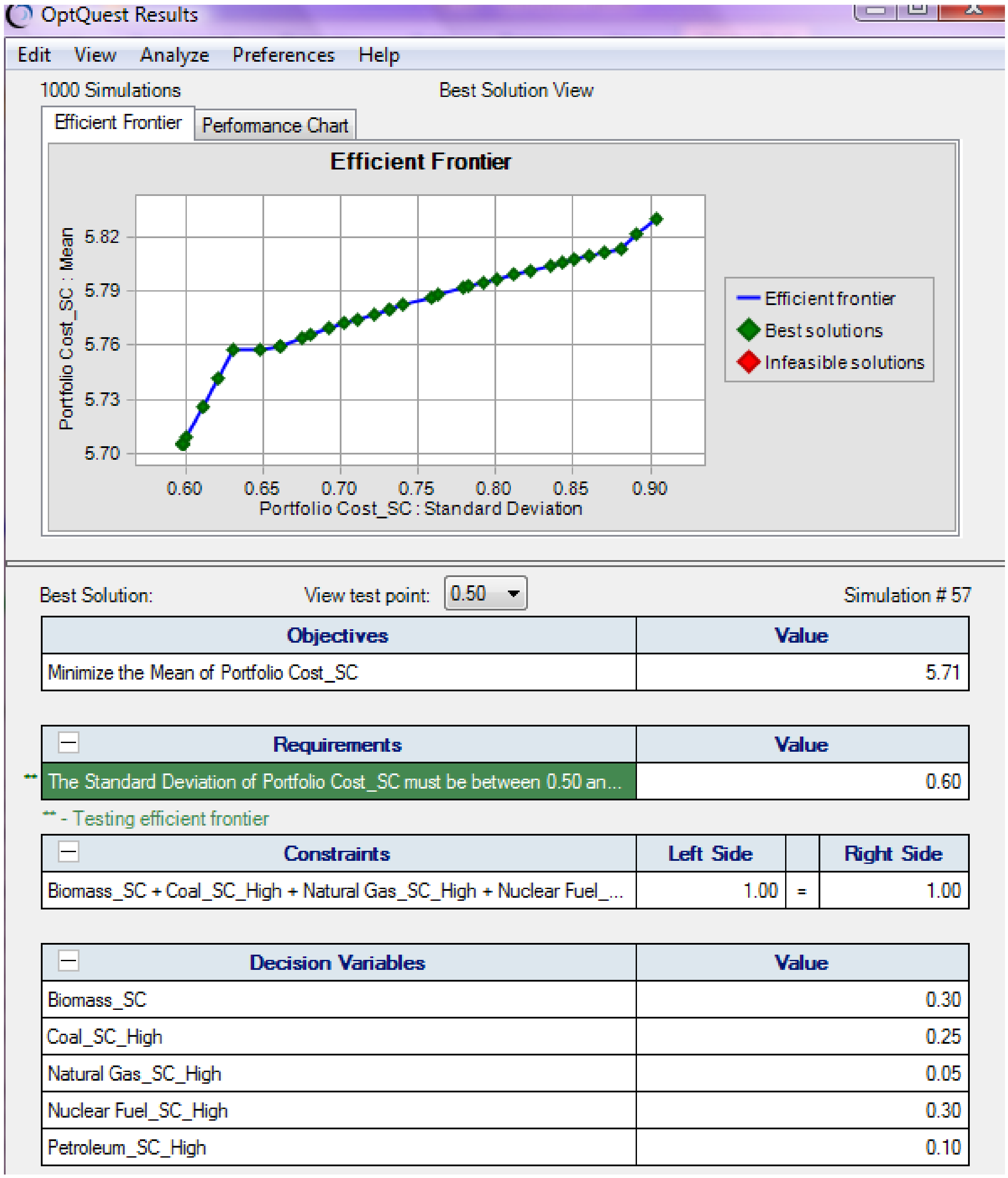


Figure 6-8: EPM simulation result at high level of social cost

Simulation results in Table 6-7 show that at different level of social costs, the optimal energy portfolio is different and favors different types of energy resources, for example, at low and central level of social costs, coal and nuclear are preferable due to the stable and lower cost; however, at high level of social cost, biomass, nuclear (only if social cost of nuclear is under 830% of its private cost) and potential natural gas will be more favored than coal and petroleum in the optimal energy portfolio. The results have demonstrated the previous analysis from Table 6-5 and 6-6, and also updated the breakdown estimates of social costs with more accurate results from 2007.

Portfolio Results	**Portfolio Cost**	**Portfolio Risk/SD**	**Biomass _SC**	**Coal _SC**	**Natural Gas _SC**	**Nuclear _SC**	**Petroleum _SC**
Optimal Portfolio_ SC Low	$3.68/ Million Btu	0.86	5%	50%	5%	30%	10%
Optimal Portfolio_ SC Central	$4.09/ Million Btu	0.56	5%	50%	5%	30%	10%
Optimal Portfolio_ SC High (a)[1]	$5.71/ Million Btu	0.6	30%	25%	5%	30%	10%
Optimal Portfolio_ SC High (b)[2]	$5.83/ Million Btu	0.9	29%	6%	26%	30%	10%
Optimal Portfolio_ SC High (c)[3]	$6.21/ Million Btu	0.87	30%	47%	5%	5%	10%

Table 6-7: Optimal energy portfolios with different level of social cost

[1] Results are the optimal energy portfolio with lowest level of risk (0.6) and high level of social cost.
[2] Results are the optimal energy portfolio with higher level of risk (0.9) and high level of social cost.
[3] Results are shown the breakdown point of nuclear that optimal portfolio will favor biomass instead of nuclear when the social cost of nuclear rises to 830% of its private cost.

According to the simulations, the social cost breakdown of coal should be 300%, because at high level of social cost of coal ($6.20/million Btu), energy consumption from coal starts to drop and switches to biomass (refer to Optimal Portfolio_ SC High (a) and Optimal Portfolio_ SC High (b) in Table 6-7). The social cost breakdown of nuclear is not 300% or 500%, but 830% (refer to Optimal Portfolio_ SC High (c) in Table 6-7); only when the social cost of nuclear rises to 830% or more than its private cost, optimal portfolio would consume nuclear at the minimum and switch to biomass. The revised breakdown for social costs is shown in Table 6-8, considered to be more accurate than breakdown estimates in Table 6-5.

	Coal	**Natural gas**	**Nuclear**
SC Breakdown	300% or $5.64/million Btu (2007 price)	N/A	830% or $3.82/million Btu (2007 price)
Portfolio Shift	Biomass (and potential natural gas)	At the minimum unless switch needed	Biomass

Table 6-8: Social Cost Breakdowns and Portfolio Shifts (Revised)[1]

In conclusion, regarding the social cost of energy, energy consumption structure varies with the level of social cost, with low and central level of social cost, optimal energy portfolio favors coal and nuclear due to their stable and lower cost; with high level of social cost, optimal energy portfolio will switch to biomass (if social cost of coal is more than 300% of its private cost or social cost of nuclear is 830% more than its private cost).

[1]Breakdown points for social cost are revised according to simulations results in Table 6-7, including all the social costs.

Chapter 7 Conclusion

As the dramatic increase of fossil fuels price, especially the price of petroleum, energy consumers are paying more and more on the energy, not only for the production, operation and maintenance of energy, but also for the social costs coming with energy consumption, various taxes for instance. Also the voices from the worries about the environmental and social impacts are getting more and more attention, renewable energy resources becomes much cleaner and more cost competitive compared to traditional energy. Then how to lower the energy cost by using different combination of the available energy resources and how social cost impacts on the energy consumption structure (portfolio) become very attractive for energy consumers, no matter for individuals, industries, or countries, These questions have been asked, analyzed and answered in this dissertation.

Chapter 3 has examined all the current topics and theories about the energy resources and consumptions, for example, the current productions and consumption of energy resources, the debate regarding the peak oil and theory, the portfolio theory and the mean-variance theory and application. All of these literatures are constructed together to develop the conceptual framework of energy portfolio management (EPM) model. Finally, the framework of EPM has been created in Chapter 4.

The EPM model is composed of three major components: available energy resources, the cost structure including the private and social cost, and the mean-variance portfolio theory. Mean-variance theory has been used widely in different areas and industries, especially electricity generation planning, but it will be very interesting to apply on the overall energy consumption management. According to mean-variance portfolio theory, this dissertation has created the formula for calculating portfolio cost and risk, and simulated using efficient frontier optimization technique to find out the optimal energy portfolio. Theoretically, EPM conceptual model is trying to select the optimal energy portfolio from the available energy resources and provide the lowest portfolio cost and less portfolio risk based on their energy costs.

The EPM conceptual model provides a framework for energy consumers to optimize the energy consumption with step-by-step guidance. Chapter 5 and 6 shows the EPM simulation in the case of United States as an example of demonstrating how EPM model works in the real world. The simulations are divided into two categories: simulation with only private cost (Chapter 5) and simulation with social cost (Chapter 6). Simulation and results with different energy cost structure are totally different, for example, simulations with only private cost in Chapter 5 are trying to find out the optimal energy portfolios for energy consumption by source and sector without considering the social cost impacts, while simulations with social cost in Chapter 6 is trying to test the sensitivity of the optimal portfolio with the increase of social costs and figure out how optimal portfolio will be impacted and changes due to the involvement of social costs.

Overall, there are three categories of findings: without social costs, with single social cost and with all social costs. First of all, main findings without considering the social cost of energy from Chapter 5 are: 1) under the circumstances of consuming energy by source, biomass and coal is favorable compared to petroleum, nuclear fuel and natural gas in the optimal portfolio (Table 5-5 and Table 5-7); 2) under the circumstances of consuming by sector, more biomass consumption instead of petroleum can lower the portfolio cost and the associated risk (Table 5-12). In brief, without considering the social cost of energy, biomass energy and coal have demonstrated the cost competitive advantages over petroleum, and natural gas, and energy consumers should consider more energy consumption from coal and biomass in order to lower portfolio cost and the risk.

Second, with only one social cost included at each simulation, energy consumption structure (optimal energy portfolio) changes with the increase of social cost: with a low level of the social costs, energy portfolio seems remain unchanged; however, when the social cost of energy reaches to a certain amount, energy portfolio starts to changes and favors lower-cost energy. For example, the social cost breakdown estimate of coal starts from 100% (Table 6-5), means when the social cost of coal rises to 100% more than its private cost, optimal portfolio starts to reduce the consumption from coal and switch to biomass, and finally drops to the minimum once the social cost of coal increases to 300%. The social cost breakdown estimate for nuclear with considering only social cost of nuclear is 300% which indicates optimal energy portfolio will favor biomass if the social cost of nuclear rises to 300% or more. In brief, coal and nuclear are still optimal choices only if the social costs are under the breakdown point; otherwise, biomass will be preferable than coal and nuclear.

Thirdly, with all sorts of social costs included simultaneously, energy consumption structure (optimal portfolio) varies with the level of social cost: with low and central level of social cost, optimal energy portfolio will favor coal and nuclear due to their stable and lower cost; with high level of social cost, biomass, nuclear and potential natural gas will be more favored than coal and petroleum; however, optimal energy portfolio will switch to favor biomass if social cost of coal is more than 300% of its private cost or social cost of nuclear is 830% more than its private cost. The results have also revised the social cost breakdown estimates (Table 6-5) with more accurate level of social cost. The social cost breakdown of coal should be 300% (at high level of social cost of coal such as $6.20/million Btu in 2007 price), and optimal energy portfolio will switch to favor biomass and potential natural gas if the social cost of coal is 300% or more than its private cost; and the social cost breakdown of nuclear is not 300% or 500%, but 830% (at high level of social cost of coal such as $3.82/million Btu in 2007 price, refer to Optimal Portfolio_ SC High (c) in Table 6-7) indicating when the social cost of nuclear rises to 830% or more than its private cost, the optimal portfolio would consume nuclear at the minimum and switch to biomass. In the case of United States, the current high level of social cost ($6.2/Million Btu in Table 6-6) shows that it has already exceeded the breakdown point, based on the results and findings, the optimal portfolio should reduce the energy consumption from coal and switch to biomass (or natural gas but with higher risk).

The major contributions of this dissertation are developing the EPM conceptual framework which shows how to lower the energy consumption using portfolio theory and optimization techniques; performing EPM simulations with and without social cost which demonstrate the selection of optimal energy choices for lowering portfolio cost, and further, the impacts of social cost on the selection of energy portfolio. Specifically, with the objective of optimizing the energy consumption, EPM model has done well in the simulations for the case of United States, and provided useful guidance for energy consumers about how to lower the portfolio cost by selecting different energy combinations, and also explained the sensitivity of the optimal portfolio with the consideration of social cost, which can offer some thoughts to energy consumers and policy decision makers about how social cost of energy will impact on the energy consumption. For further studies and researches, EPM model also provides a very good framework and simulation example, and can be applied and scalable for various countries, depending upon parameterization of variables for the country.

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Appendix

Appendix 1: Summary of MVP Applications

Summary of MVP Applications						
Level	**Targets**	**Resources**	**Method**	**Cost**	**Risk**	**Reference**
State: Virginia	Electricity generating planning	RE+TE: Coal, oil, natural gas, nuclear, hydro, wood, MSW, landfill gas, Other biomass, wind, solar, imports	MVP+EF	capital cost/ investment, fixed and variable O&M cost, fuel cost)	standard deviation of each cost component	DeLaquil et al. (2005)
State: California	Electricity generating planning	RE+TE: Coal, biomass, natural gas, nuclear, hydro, wind, solar thermal, biogas, solar PV, geothermal	MVP+ EF	capital, operating and maintenance, fuel, CO_2 costs per unit of output for each technology	standard deviation of each cost component	Lesser et al. (2007)
Country: Cyprus	Electricity generating planning	RE+TE: oil, natural gas, coal and wind	MVP+EF	Fuel cost, Operating and Maintenance (O&M) cost, Capital or Construction cost, CO_2 cost and System Integration cost	Holding-period returns HPR standard deviation	Rodoulis (2010)
Country: UK	Electricity generating planning	TE: Coal, gas(CCGT) and nuclear power	MVP+ Monte Carlo Simulation (MCS)+EF	capital, fuel, fixed and variable O&M, nuclear waste fee and overnight and CO_2 cost	standard deviation of the ENPV per unit of capacity (per GWe)	Roques et al. (2006)

Multinational: Austria, Denmark, France, Germany and Spain	Wind power planning	RE: wind	MVP+EF	return: wind power output referred as average capacity factor	standard deviation of wind power output variation of hourly wind power production	Roques et al. (2009)
EU, US, Mexico	Electricity generating planning	TE+RE: coal, oil, nuclear, gas, wind, hydro, geothermal	MVP+EF	Fuel cost, Operating and Maintenance (O&M) cost, Construction cost,	the standard deviation of each cost	Awerbuch (2004)
Country: Tunisia	Electricity generating planning	TE+RE: turbine oil, gas, biogas, wind, PV, hydro, etc	MVP+EF	Fixed Operating and Maintenance (O&M) cost, Construction cost,	standard deviation	Awerbuch et al. (2005)
Country: Western US	Electricity generating planning	TE+RE: Coal, oil, nuclear, wind, Hydro and geothermal	MVP+EF	fuel, fixed& variable O&M, construction or capital	Standard deviation of technology generating costs.	Awerbuch et al. (2005)

Appendix 2: U.S. Energy Consumption (percentage) by Source: 1949-2009

U.S. Energy Consumption (percentage) by Source: 1949-2009											
Year	**Coal**	**Natural Gas**	**Petroleum**	**Nuclear Electric Power**	**Hydro-electric power**	**Geothermal**	**Solar/PV**	**Wind**	**Biomass**	**RE total**	**Total**
1949	37.44%	16.09%	37.15%	0.00%	4.45%	N/A	N/A	N/A	4.84%	9.30%	99.98%
1950	35.67%	17.24%	38.47%	0.00%	4.09%	N/A	N/A	N/A	4.51%	8.60%	99.98%
1951	33.89%	19.06%	39.02%	0.00%	3.85%	N/A	N/A	N/A	4.15%	8.00%	99.98%
1952	30.74%	20.54%	40.70%	0.00%	3.99%	N/A	N/A	N/A	4.01%	8.00%	99.98%
1953	30.17%	20.99%	41.30%	0.00%	3.75%	N/A	N/A	N/A	3.77%	7.52%	99.98%
1954	26.50%	22.74%	43.23%	0.00%	3.71%	N/A	N/A	N/A	3.81%	7.52%	99.98%
1955	27.75%	22.38%	42.91%	0.00%	3.38%	N/A	N/A	N/A	3.54%	6.92%	99.97%
1956	27.15%	23.03%	42.96%	0.00%	3.44%	N/A	N/A	N/A	3.39%	6.83%	99.96%
1957	25.85%	24.39%	42.91%	0.00%	3.63%	N/A	N/A	N/A	3.19%	6.82%	99.97%
1958	22.88%	25.60%	44.49%	0.00%	3.82%	N/A	N/A	N/A	3.18%	7.00%	99.97%
1959	21.88%	26.96%	44.45%	0.01%	3.56%	N/A	N/A	N/A	3.11%	6.68%	99.97%
1960	21.81%	27.47%	44.18%	0.01%	3.57%	0.00%	N/A	N/A	2.93%	6.50%	99.97%
1961	21.02%	28.26%	44.20%	0.04%	3.62%	0.00%	N/A	N/A	2.83%	6.46%	99.98%
1962	20.70%	28.71%	44.01%	0.06%	3.80%	0.00%	N/A	N/A	2.72%	6.52%	100.00%
1963	20.96%	29.01%	43.71%	0.08%	3.57%	0.01%	N/A	N/A	2.67%	6.24%	100.00%
1964	21.14%	29.50%	43.04%	0.08%	3.64%	0.01%	N/A	N/A	2.58%	6.23%	99.99%
1965	21.40%	29.19%	43.03%	0.08%	3.81%	0.01%	N/A	N/A	2.47%	6.29%	100.00%
1966	21.25%	29.81%	42.80%	0.11%	3.62%	0.01%	N/A	N/A	2.40%	6.02%	99.99%
1967	20.20%	30.46%	42.92%	0.15%	3.98%	0.01%	N/A	N/A	2.28%	6.27%	100.00%
1968	19.73%	30.78%	43.22%	0.23%	3.76%	0.02%	N/A	N/A	2.27%	6.05%	100.00%
1969	18.81%	31.51%	43.18%	0.23%	4.04%	0.02%	N/A	N/A	2.20%	6.25%	99.99%
1970	17.99	32.12%	43.51	0.35%	3.88%	0.02%	N/A	N/A	2.11%	6.01	99.99

	%		%							%	%
1971	16.69 %	32.43%	44.11 %	0.60%	4.08%	0.02%	N/A	N/A	2.07%	6.16 %	99.98 %
1972	16.58 %	31.22%	45.32 %	0.80%	3.94%	0.04%	N/A	N/A	2.07%	6.05 %	99.96 %
1973	17.12 %	29.74%	46.02 %	1.20%	3.78%	0.06%	N/A	N/A	2.02%	5.86 %	99.94 %
1974	17.19 %	29.37%	45.21 %	1.72%	4.29%	0.07%	N/A	N/A	2.08%	6.45 %	99.94 %
1975	17.61 %	27.71%	45.46 %	2.64%	4.38%	0.10%	N/A	N/A	2.08%	6.56 %	99.97 %
1976	17.87 %	26.77%	46.27 %	2.78%	3.92%	0.10%	N/A	N/A	2.25%	6.27 %	99.96 %
1977	17.87 %	25.55%	47.59 %	3.46%	2.99%	0.10%	N/A	N/A	2.36%	5.45 %	99.92 %
1978	17.37 %	25.00%	47.46 %	3.78%	3.67%	0.08%	N/A	N/A	2.55%	6.30 %	99.92 %
1979	18.67 %	25.54%	45.89 %	3.43%	3.62%	0.10%	N/A	N/A	2.66%	6.39 %	99.91 %
1980	19.70 %	25.90%	43.78 %	3.51%	3.71%	0.14%	N/A	N/A	3.17%	7.02 %	99.91 %
1981	20.86 %	25.93%	41.92 %	3.95%	3.62%	0.16%	N/A	N/A	3.41%	7.19 %	99.85 %
1982	20.92 %	25.09%	41.33 %	4.28%	4.46%	0.14%	N/A	N/A	3.64%	8.25 %	99.86 %
1983	21.74 %	23.58%	41.15 %	4.38%	4.83%	0.18%	N/A	0.00%	3.98%	8.98 %	99.83 %
1984	22.24 %	23.98%	40.48 %	4.63%	4.41%	0.21%	0.00%	0.00%	3.87%	8.50 %	99.82 %
1985	22.83 %	23.14%	40.43 %	5.33%	3.88%	0.26%	0.00%	0.00%	3.94%	8.09 %	99.82 %
1986	22.47 %	21.62%	41.95 %	5.71%	4.00%	0.29%	0.00%	0.00%	3.82%	8.11 %	99.84 %
1987	22.76 %	22.28%	41.51 %	6.00%	3.33%	0.29%	0.00%	0.00%	3.63%	7.25 %	99.80 %
1988	22.80 %	22.28%	41.32 %	6.75%	2.82%	0.26%	0.00%	0.00%	3.64%	6.72 %	99.87 %
1989	22.49 %	23.08%	40.28 %	6.60%	3.34%	0.37%	0.07%	0.03%	3.72%	7.52 %	99.96 %
1990	22.65 %	23.16%	39.64 %	7.21%	3.60%	0.40%	0.07%	0.03%	3.23%	7.33 %	99.99 %
1991	22.46 %	23.68%	38.82 %	7.59%	3.56%	0.41%	0.07%	0.04%	3.29%	7.37 %	99.92 %
1992	22.29 %	24.10%	39.00 %	7.54%	3.05%	0.41%	0.07%	0.03%	3.41%	6.97 %	99.90 %
1993	22.67 %	24.23%	38.52 %	7.32%	3.30%	0.42%	0.08%	0.04%	3.32%	7.15 %	99.89 %
1994	22.37	24.34%	38.72	7.50%	3.01%	0.38%	0.08%	0.04%	3.39%	6.89	99.83

	%		%							%	%
1995	22.10%	24.87%	37.77%	7.76%	3.52%	0.32%	0.08%	0.04%	3.40%	7.35%	99.85%
1996	22.33%	24.51%	37.88%	7.53%	3.81%	0.34%	0.08%	0.04%	3.35%	7.61%	99.85%
1997	22.68%	24.51%	38.16%	6.96%	3.84%	0.34%	0.07%	0.04%	3.28%	7.57%	99.88%
1998	22.82%	23.99%	38.68%	7.43%	3.46%	0.34%	0.07%	0.03%	3.08%	6.99%	99.91%
1999	22.39%	23.66%	39.08%	7.86%	3.38%	0.34%	0.07%	0.05%	3.06%	6.90%	99.90%
2000	22.88%	24.07%	38.66%	7.94%	2.84%	0.32%	0.07%	0.06%	3.04%	6.32%	99.88%
2001	22.78%	23.64%	39.65%	8.34%	2.33%	0.32%	0.07%	0.07%	2.72%	5.51%	99.92%
2002	22.45%	24.08%	39.06%	8.32%	2.75%	0.34%	0.07%	0.11%	2.76%	6.02%	99.93%
2003	22.80%	23.27%	39.55%	8.11%	2.88%	0.34%	0.06%	0.12%	2.86%	6.26%	99.98%
2004	22.53%	22.84%	40.17%	8.20%	2.68%	0.34%	0.06%	0.14%	3.00%	6.23%	99.96%
2005	22.74%	22.46%	40.21%	8.12%	2.69%	0.34%	0.07%	0.18%	3.10%	6.38%	99.92%
2006	22.56%	22.27%	40.04%	8.23%	2.88%	0.34%	0.07%	0.26%	3.28%	6.84%	99.94%
2007	22.43%	23.35%	39.17%	8.33%	2.41%	0.34%	0.08%	0.34%	3.45%	6.62%	99.89%
2008	22.56%	23.93%	37.50%	8.48%	2.53%	0.36%	0.10%	0.55%	3.88%	7.41%	99.89%
2009	20.87%	24.70%	37.29%	8.83%	2.84%	0.39%	0.11%	0.74%	4.11%	8.19%	99.88%

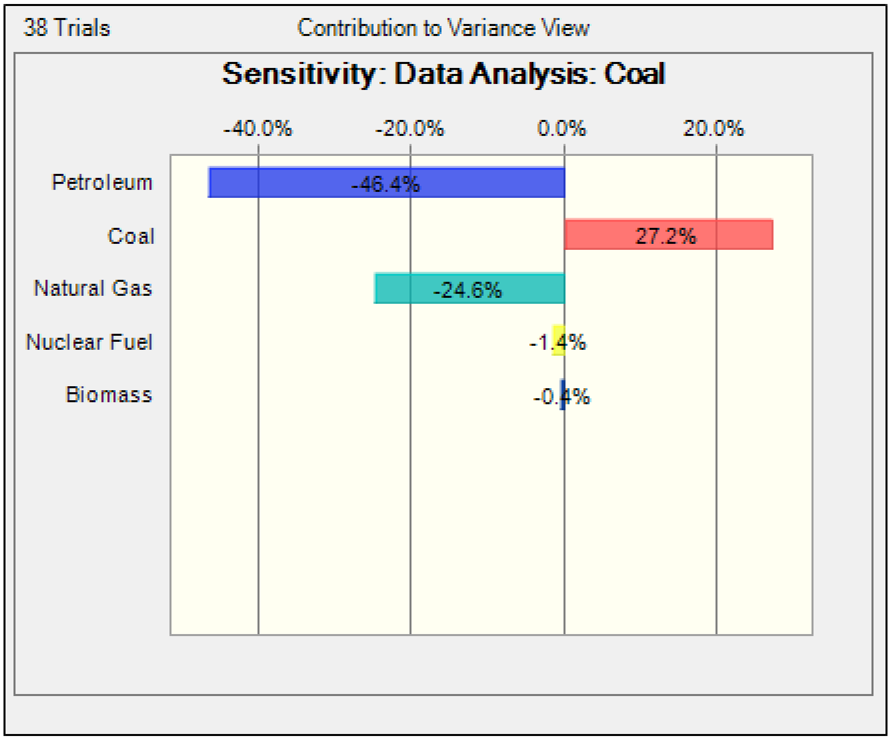
Appendix 3: Energy Cost (Consumer Price) by Source: 1970-2007

	Energy Cost (Consumer Price) by Source (Dollars per Million Btu)				
Year	**Petroleum**	**Coal**	**Natural Gas**	**Nuclear Fuel**	**Biomass**
1970	1.33	0.38	0.59	0.18	1.29
1971	1.40	0.42	0.63	0.18	1.31
1972	1.42	0.45	0.68	0.18	1.33
1973	1.64	0.48	0.73	0.19	1.39
1974	2.60	0.88	0.89	0.2	1.5
1975	2.86	1.03	1.18	0.24	1.5
1976	3.01	1.04	1.46	0.25	1.53
1977	3.32	1.11	1.76	0.27	1.58
1978	3.42	1.27	1.95	0.3	1.61
1979	4.62	1.36	2.31	0.34	1.88
1980	6.58	1.46	2.86	0.43	2.26
1981	7.72	1.64	3.43	0.48	2.52
1982	7.43	1.73	4.23	0.54	2.6
1983	7.04	1.7	4.72	0.58	2.44
1984	6.99	1.71	4.75	0.67	2.53
1985	6.76	1.69	4.61	0.71	2.47
1986	5.17	1.62	4.07	0.7	2.12
1987	5.30	1.53	3.77	0.71	2.07
1988	5.08	1.5	3.78	0.73	2.09
1989	5.43	1.48	3.82	0.7	1.42
1990	6.37	1.49	3.82	0.67	1.32
1991	6.04	1.48	3.74	0.63	1.39
1992	5.76	1.45	3.83	0.59	1.32
1993	5.70	1.42	4.1	0.56	1.28
1994	5.73	1.39	4.08	0.56	1.39
1995	5.83	1.37	3.73	0.54	1.4

1996	6.59	1.33	4.25	0.51	1.25
1997	6.37	1.32	4.53	0.51	1.15
1998	5.26	1.29	4.13	0.5	1.27
1999	5.83	1.27	4.16	0.48	1.34
2000	8.24	1.24	5.62	0.46	1.58
2001	7.70	1.29	6.87	0.44	2.08
2002	7.21	1.3	5.27	0.43	2.19
2003	8.59	1.32	7	0.42	1.98
2004	10.24	1.41	7.95	0.42	2.17
2005	13.21	1.62	9.92	0.43	3.1
2006	15.27	1.78	9.62	0.44	3.14
2007	16.70	1.88	9.3	0.46	3.35

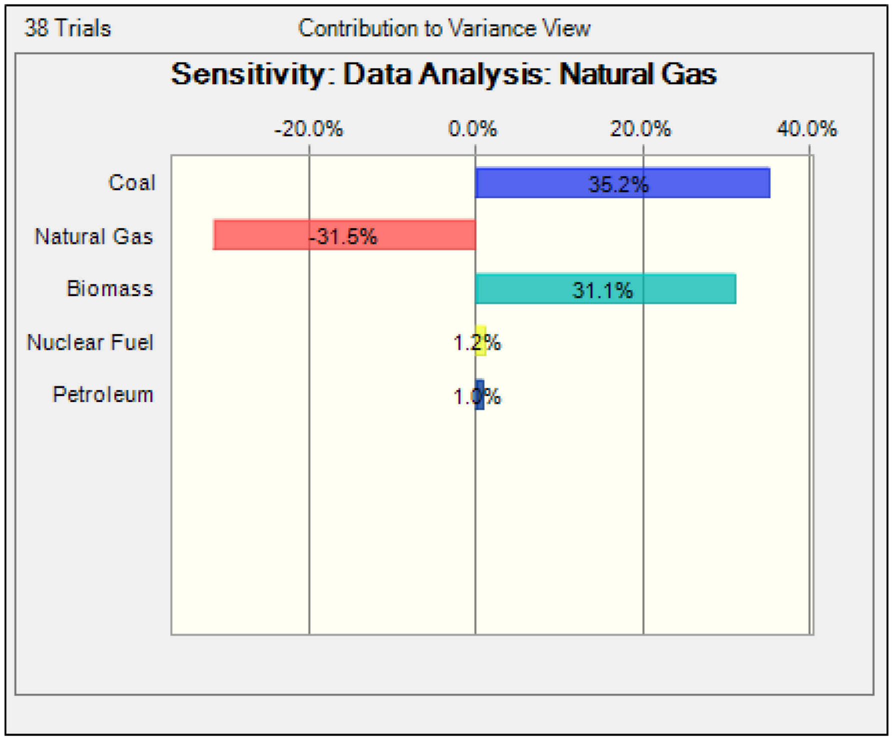
Appendix 4: Sensitivity Analysis for EMP Simulation by Source

Coal Sensitivity Analysis:



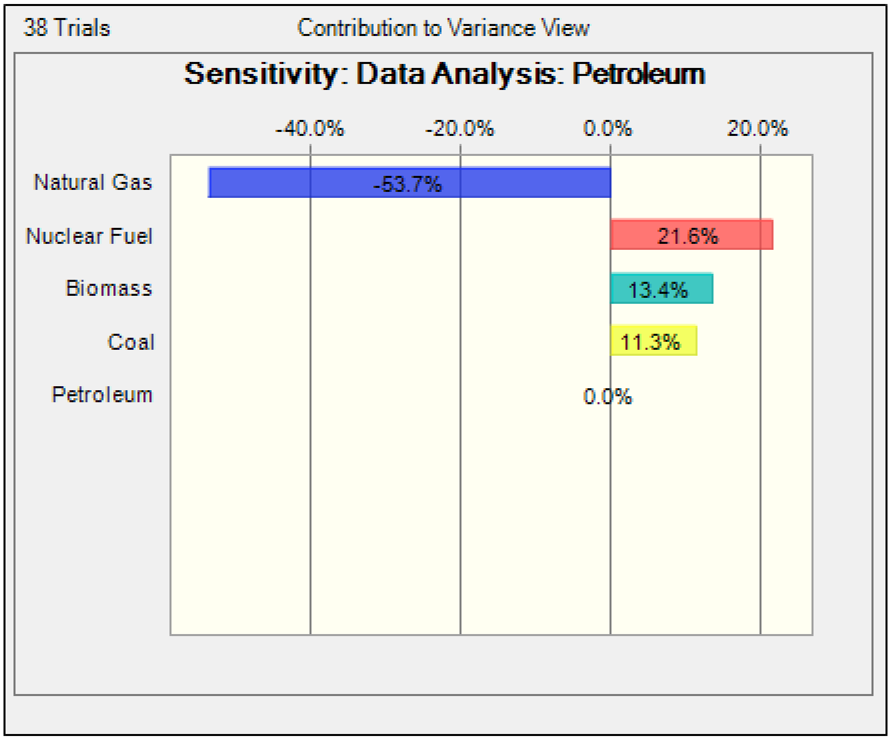
Sensitivity: Data Analysis: Coal		
Assumptions	Contribution To Variance	Rank Correlation
Petroleum	46.38%	-0.24
Coal	27.22%	0.18
Natural Gas	24.62%	-0.17
Nuclear Fuel	1.36%	-0.04
Biomass	0.41%	-0.02

Natural Gas Sensitivity Analysis:



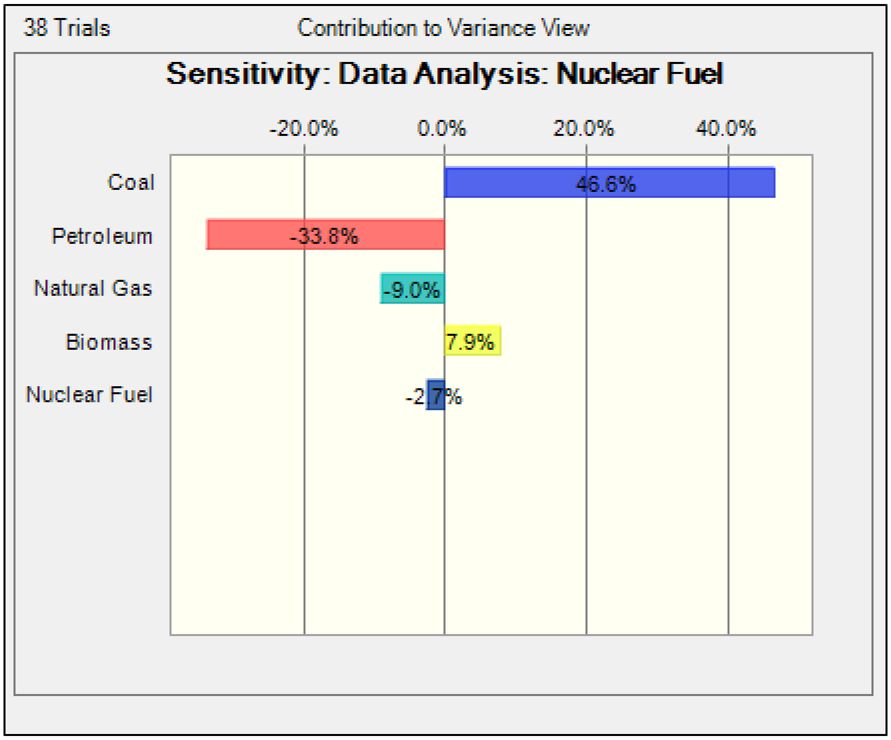
Sensitivity: Data Analysis: Natural Gas		
Assumptions	Contribution To Variance	Rank Correlation
Coal	35.21%	0.11
Natural Gas	31.47%	-0.11
Biomass	31.09%	0.11
Nuclear Fuel	1.23%	0.02
Petroleum	1.00%	0.02

Petroleum Sensitivity Analysis:



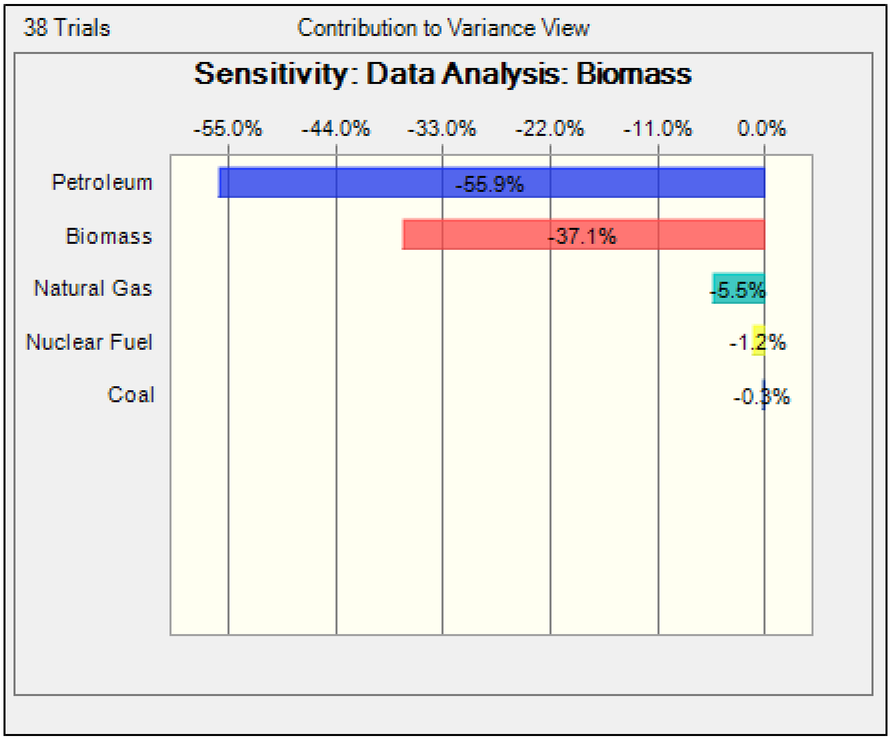
Sensitivity: Data Analysis: Petroleum		
Assumptions	Contribution To Variance	Rank Correlation
Natural Gas	53.69%	-0.20
Nuclear Fuel	21.57%	0.13
Biomass	13.41%	0.10
Coal	11.33%	0.09
Petroleum	0.01%	0.00

Nuclear Fuel Sensitivity Analysis:



Sensitivity: Data Analysis: Nuclear Fuel		
Assumptions	Contribution To Variance	Rank Correlation
Coal	46.57%	0.18
Petroleum	33.81%	-0.15
Natural Gas	9.05%	-0.08
Biomass	7.92%	0.07
Nuclear Fuel	2.65%	-0.04

Biomass Sensitivity Analysis:



Sensitivity: Data Analysis: Biomass		
Assumptions	Contribution To Variance	Rank Correlation
Petroleum	55.91%	-0.19
Biomass	37.10%	-0.16
Natural Gas	5.46%	-0.06
Nuclear Fuel	1.19%	-0.03
Coal	0.34%	-0.01

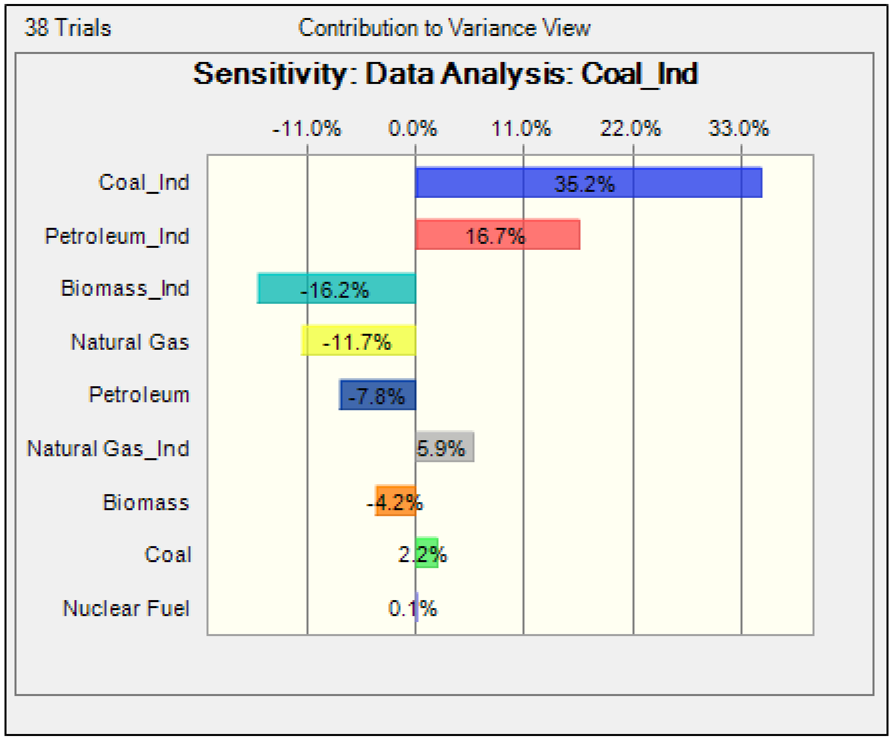
Appendix 5: Energy Cost (Consumer Price) by Sector: 1970-2007

	Industrial Sector (Dollars per Million Btu)			
Year	**Coal**	**Natural Gas**	**Petroleum**	**Biomass**
1970	0.45	0.38	0.98	1.59
1971	0.5	0.41	1.05	1.59
1972	0.55	0.46	1.05	1.59
1973	0.63	0.5	1.18	1.6
1974	1.22	0.67	2.24	1.6
1975	1.5	0.95	2.46	1.6
1976	1.5	1.21	2.57	1.6
1977	1.56	1.48	2.84	1.59
1978	1.73	1.66	2.96	1.6
1979	1.75	1.96	3.99	1.6
1980	1.87	2.52	5.75	1.67
1981	2.06	3.07	6.84	1.67
1982	2.09	3.8	6.51	1.67
1983	1.91	4.1	6.57	1.67
1984	1.91	4.13	6.56	1.67
1985	1.9	3.87	6.29	1.67
1986	1.8	3.2	4.92	1.65
1987	1.67	2.88	4.96	1.65
1988	1.68	2.9	4.62	1.65
1989	1.68	2.93	4.69	1.2
1990	1.69	2.95	5.48	0.99
1991	1.67	2.8	5.31	1.14
1992	1.69	2.91	5	1.13
1993	1.63	3.12	4.93	1.12
1994	1.62	3.09	5.04	1.15
1995	1.63	2.8	5.2	1.21
1996	1.62	3.3	6.04	1.01

1997	1.62	3.53	5.68	1.01
1998	1.58	3.16	4.54	1.24
1999	1.58	3.21	5.07	1.38
2000	1.55	4.61	7.26	1.43
2001	1.63	5.71	6.75	1.95
2002	1.75	4.37	6.43	2.11
2003	1.74	6.03	7.78	1.62
2004	1.99	7.08	9.32	1.79
2005	2.56	9.07	11.85	2.73
2006	2.83	8.75	14.14	2.65
2007	2.91	8.28	15.75	2.52

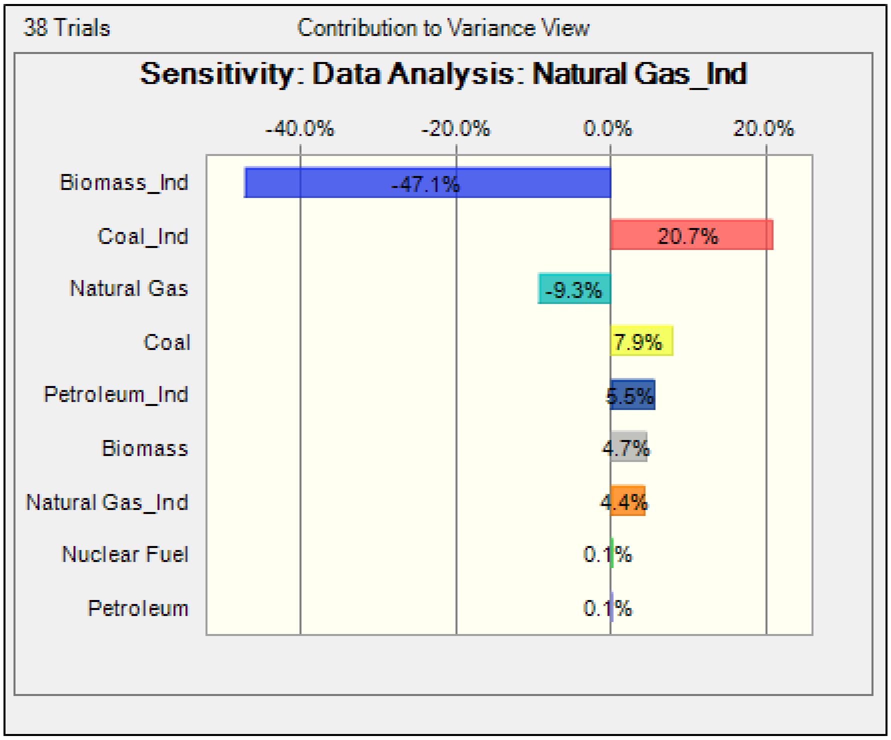
Appendix 6: Sensitivity Analysis for EPM Simulation by Sector

Coal_ Ind Sensitivity Analysis:



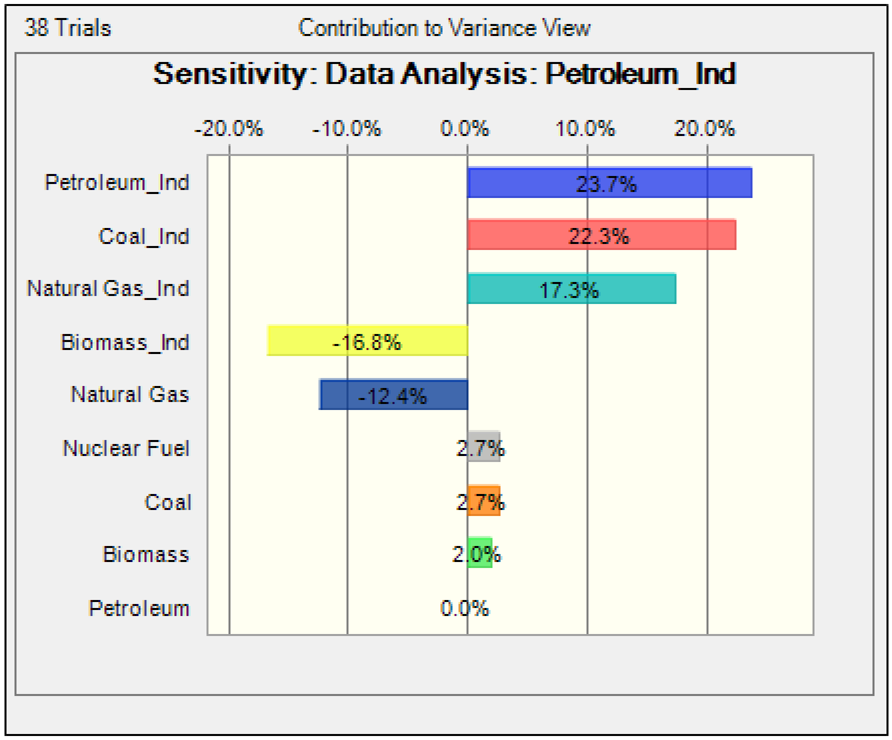
Sensitivity: Data Analysis: Coal_Ind		
Assumptions	Contribution To Variance	Rank Correlation
Coal_Ind	35.18%	0.46
Petroleum_Ind	16.67%	0.32
Biomass_Ind	16.20%	-0.31
Natural Gas	11.70%	-0.27
Petroleum	7.81%	-0.22
Natural Gas_Ind	5.87%	0.187811485
Biomass	4.21%	-0.159119585
Coal	2.23%	0.115862712
Nuclear Fuel	0.13%	0.03

Natural Gas_ Ind Sensitivity Analysis:



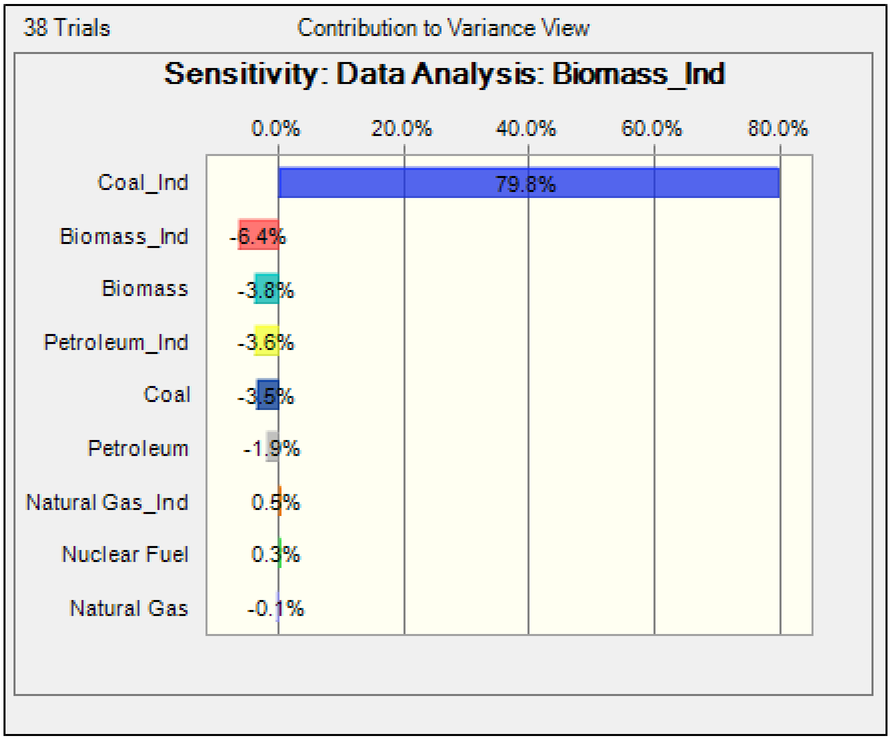
Sensitivity: Data Analysis: Natural Gas_Ind		
Assumptions	Contribution To Variance	Rank Correlation
Biomass_Ind	47.13%	-0.28
Coal_Ind	20.71%	0.185260163
Natural Gas	9.31%	-0.124199814
Coal	7.94%	0.114679652
Petroleum_Ind	5.53%	0.10
Biomass	4.69%	0.09
Natural Gas_Ind	4.42%	0.09
Nuclear Fuel	0.14%	0.02
Petroleum	0.14%	0.01

Petroleum_ Ind Sensitivity Analysis:



Sensitivity: Data Analysis: Petroleum_Ind		
Assumptions	Contribution To Variance	Rank Correlation
Petroleum_Ind	23.74%	0.29
Coal_Ind	22.33%	0.28
Natural Gas_Ind	17.30%	0.25
Biomass_Ind	16.78%	-0.25
Natural Gas	1.24E-01	-0.21
Nuclear Fuel	2.72%	0.09903157
Coal	2.70%	0.098593861
Biomass	2.00%	0.084915468
Petroleum	1.08E-05	-0.001969689

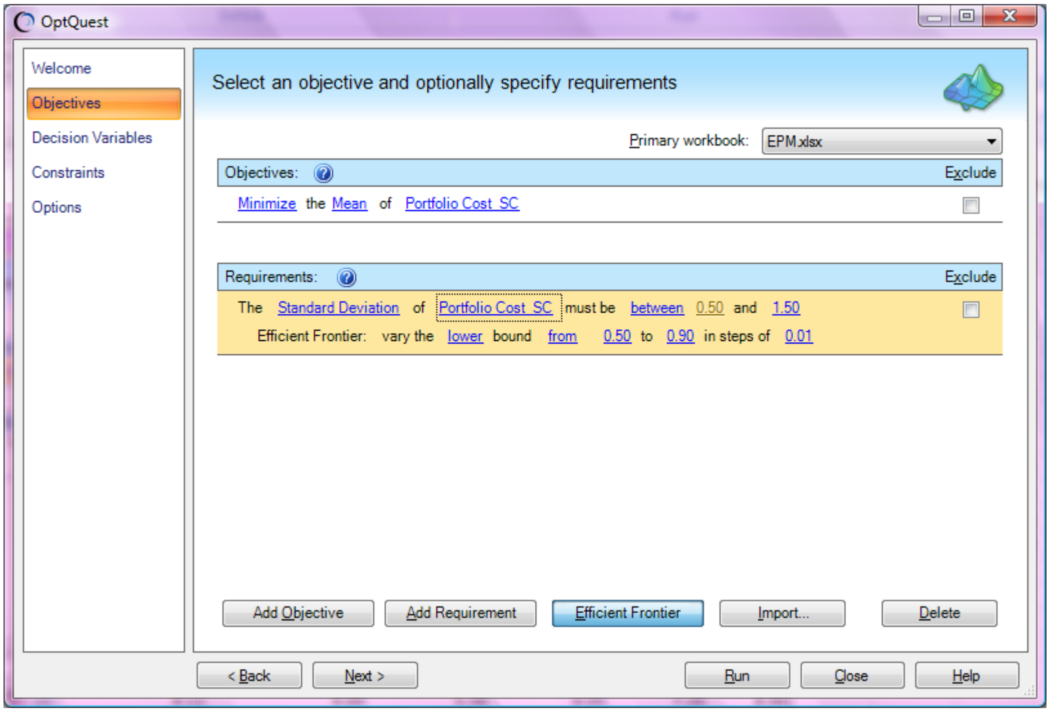
Biomass_ Ind Sensitivity Analysis:

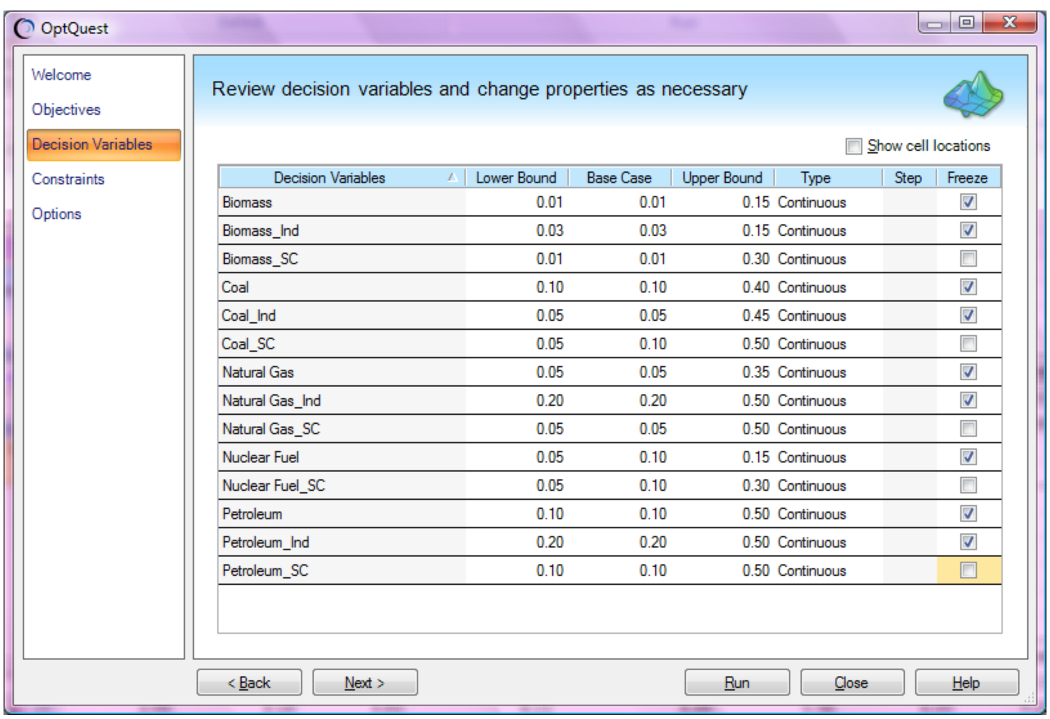


Sensitivity: Data Analysis: Biomass_Ind		
Assumptions	Contribution To Variance	Rank Correlation
Coal_Ind	79.75%	0.454465467
Biomass_Ind	6.38%	-0.128512368
Biomass	3.81%	-0.099379967
Petroleum_Ind	3.62%	-0.096851494
Coal	3.55%	-0.095862092
Petroleum	1.94%	-0.070797233
Natural Gas_Ind	0.48%	0.035288683
Nuclear Fuel	0.34%	0.029792003
Natural Gas	0.13%	-0.018139043

Appendix 7: EPM Scenario Simulation with Social Cost_ Coal

Scenario One (Coal_ SC): With no social cost of coal added





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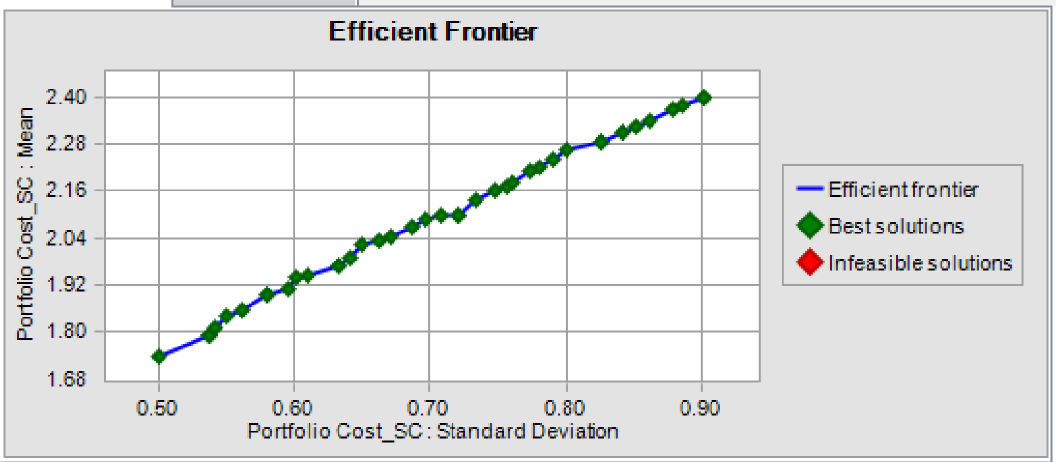
Best Solution View

Efficient Frontier | Performance Chart



Best Solution: View test point: 0.50 Simulation # 523

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	1.74

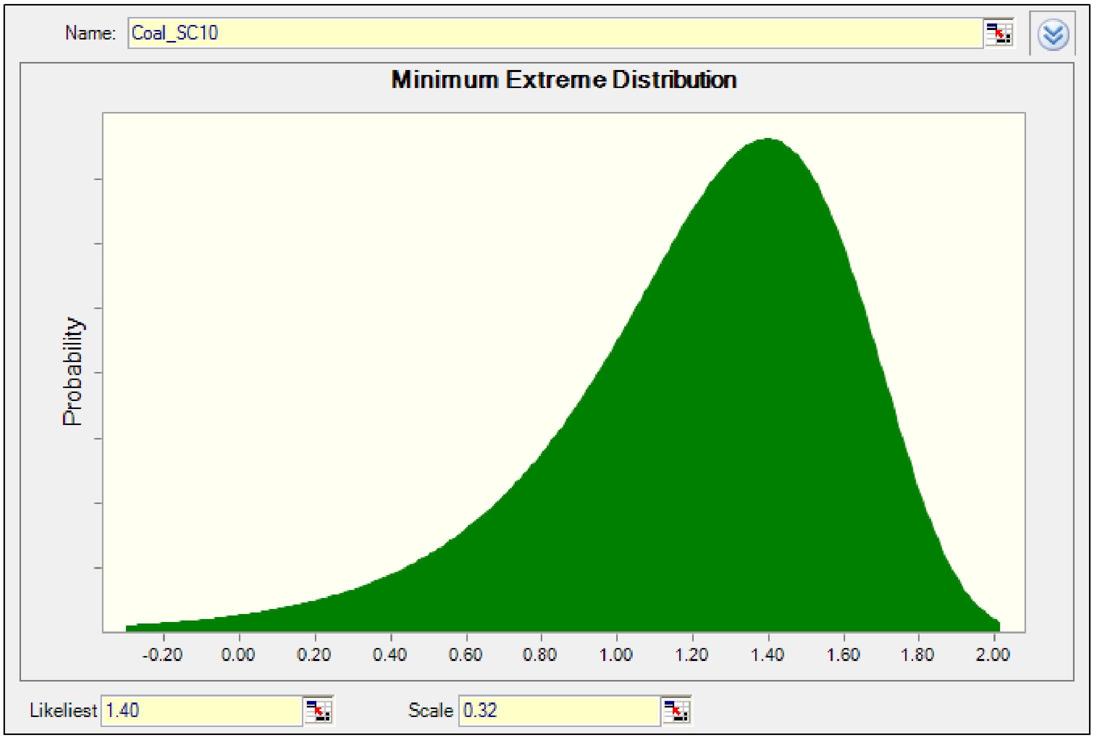
Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.50

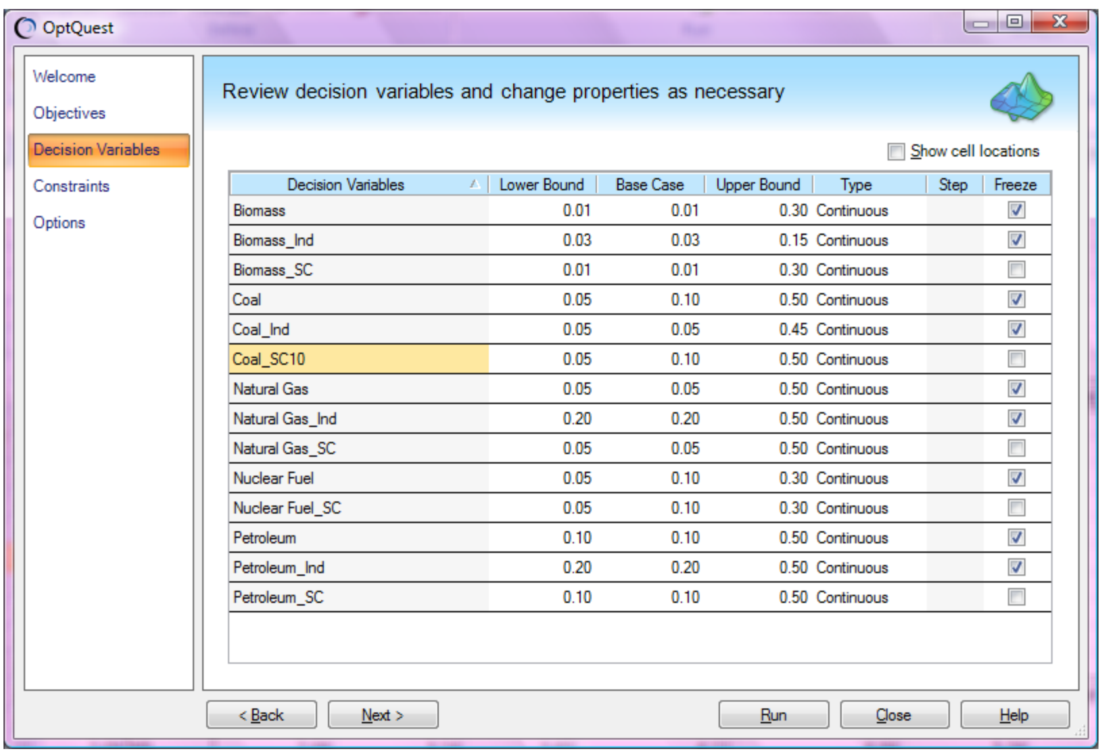
** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC + Natural Gas_SC + Nuclear Fuel_SC + Petrole...	1.00	=	1.00

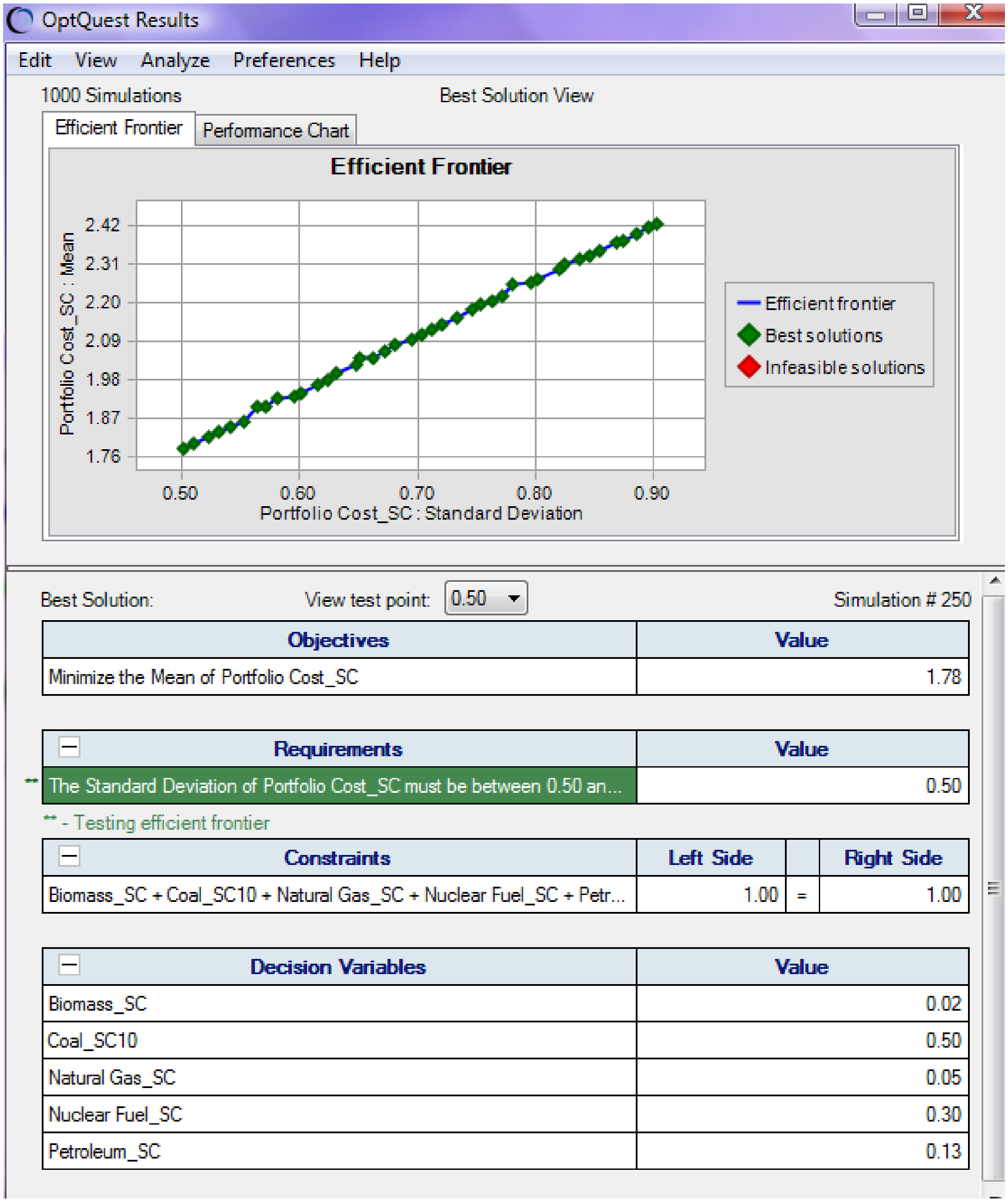
Decision Variables	Value
Biomass_SC	0.02
Coal_SC	0.50
Natural Gas_SC	0.05
Nuclear Fuel_SC	0.30
Petroleum_SC	0.13

Scenario Two (Coal_SC10): With 10% Social Cost

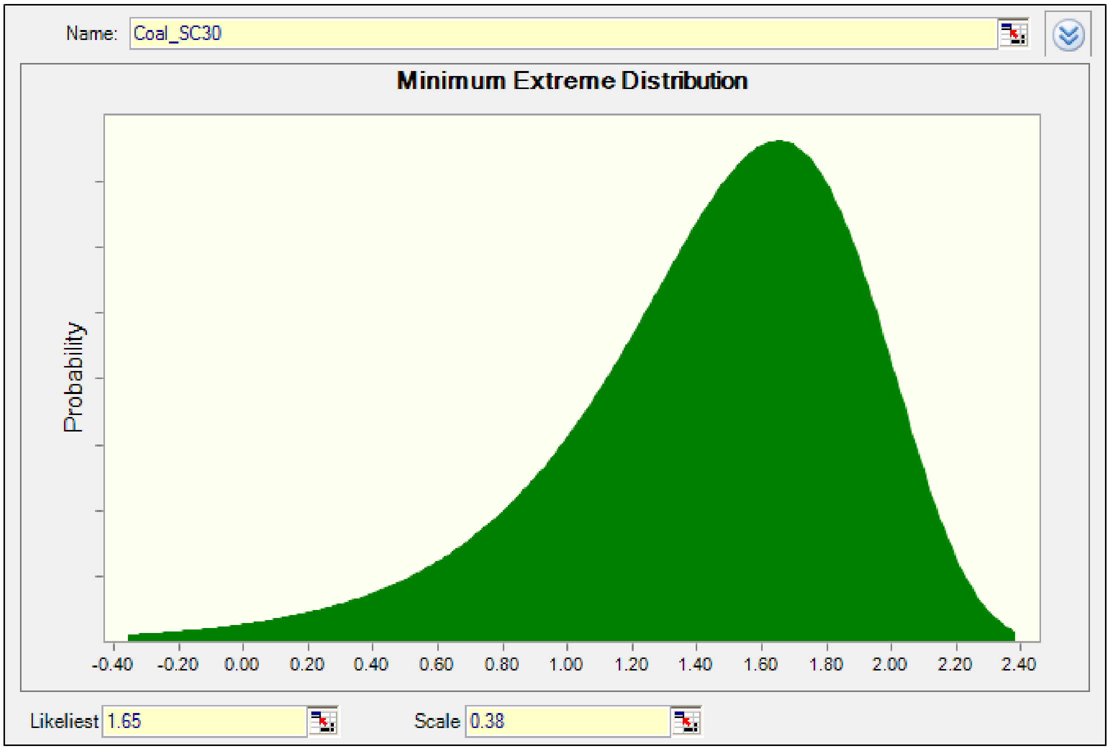


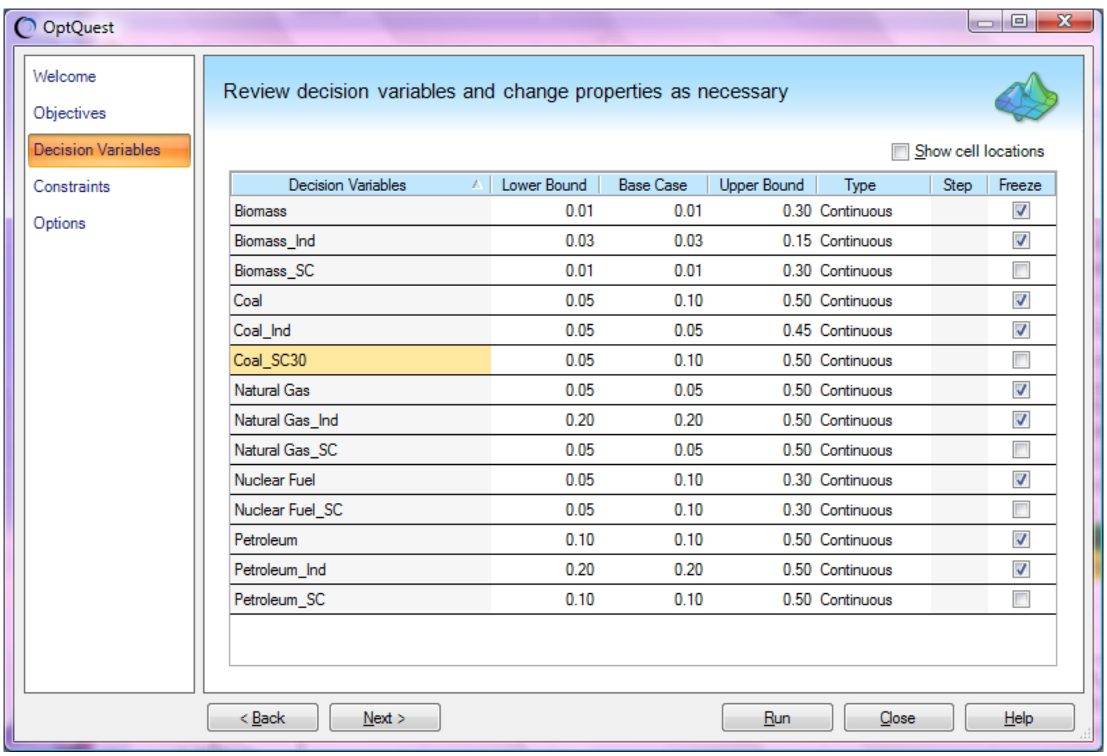


Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC10	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐


OptQuest Results
Edit View Analyze Preferences Help
1000 Simulations
Best Solution View
Efficient Frontier
Performance Chart
Efficient Frontier
Portfolio Cost_SC : Mean
2.42
2.31
2.20
2.09
1.98
1.87
1.76
0.50
0.60
0.70
0.80
0.90
Portfolio Cost_SC : Standard Deviation
Efficient frontier
Best solutions
Infeasible solutions
Best Solution:
View test point: 0.50
Simulation # 250
Objectives
Value
Minimize the Mean of Portfolio Cost_SC
1.78
Requirements
Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...
0.50
** - Testing efficient frontier
Constraints
Left Side
Right Side
Biomass_SC + Coal_SC10 + Natural Gas_SC + Nuclear Fuel_SC + Petr...
1.00
=
1.00
Decision Variables
Value
Biomass_SC
0.02
Coal_SC10
0.50
Natural Gas_SC
0.05
Nuclear Fuel_SC
0.30
Petroleum_SC
0.13

Scenario Three (Coal_SC30): With 30% Social Cost





OptQuest Results

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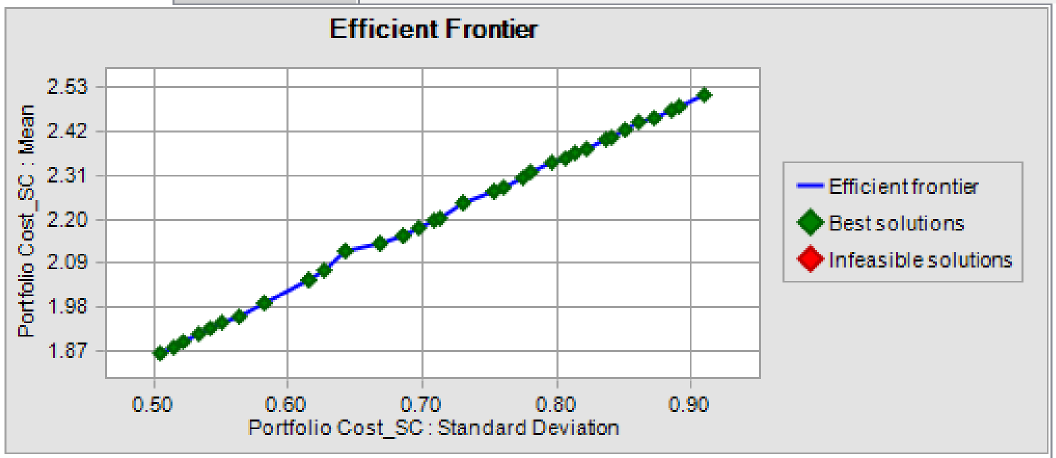
1000 Simulations

Best Solution View

Efficient Frontier | Performance Chart



Best Solution: View test point: 0.50 Simulation # 343

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	1.87

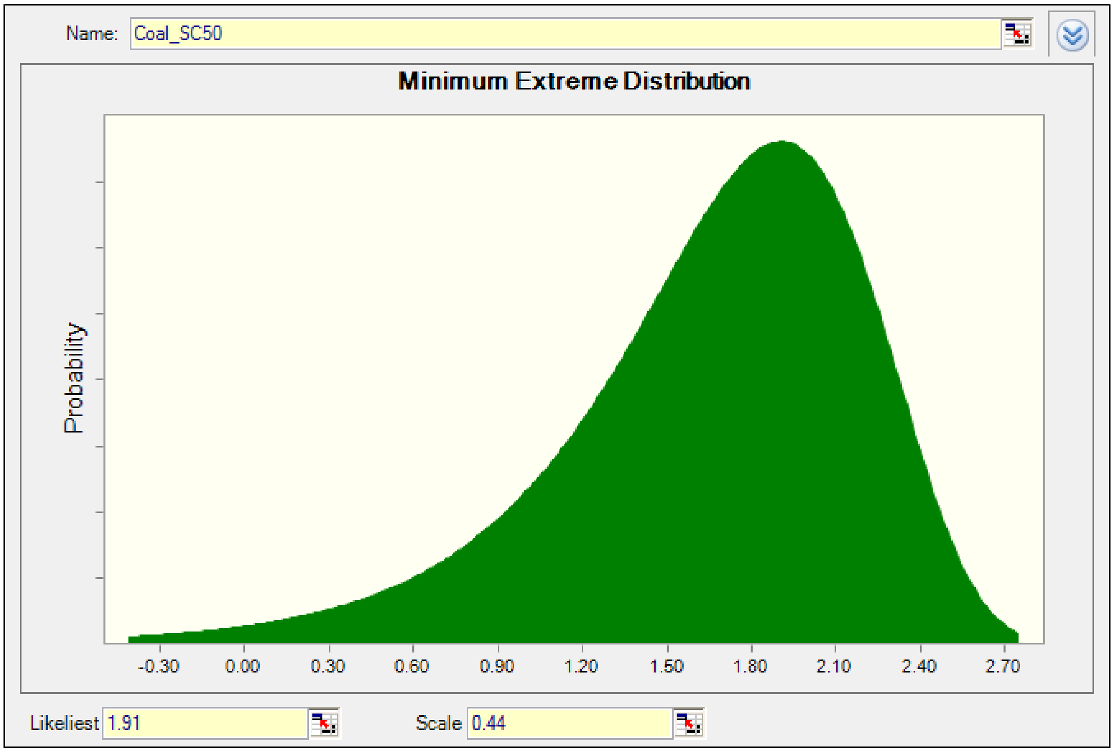
Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.50

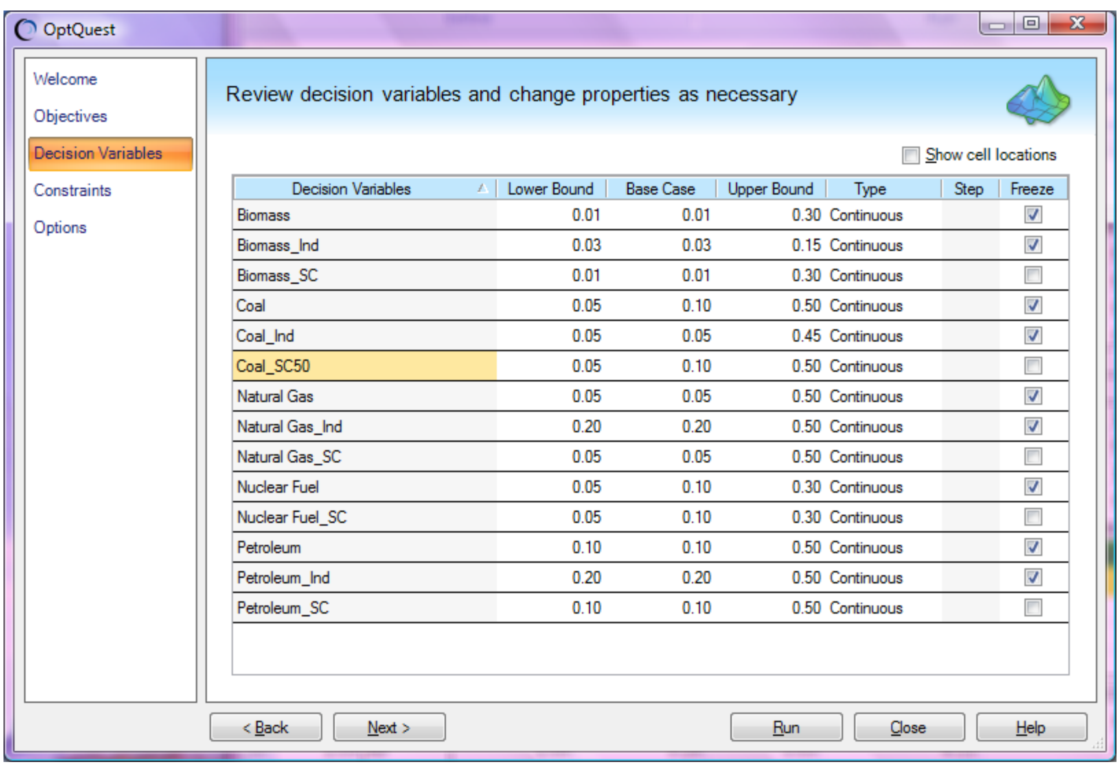
** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC30 + Natural Gas_SC + Nuclear Fuel_SC + Petr...	1.00	=	1.00

Decision Variables	Value
Biomass_SC	0.03
Coal_SC30	0.50
Natural Gas_SC	0.05
Nuclear Fuel_SC	0.30
Petroleum_SC	0.12

Scenario Four (Coal_SC50): With 50% Social Cost





Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC50	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐

OptQuest Results

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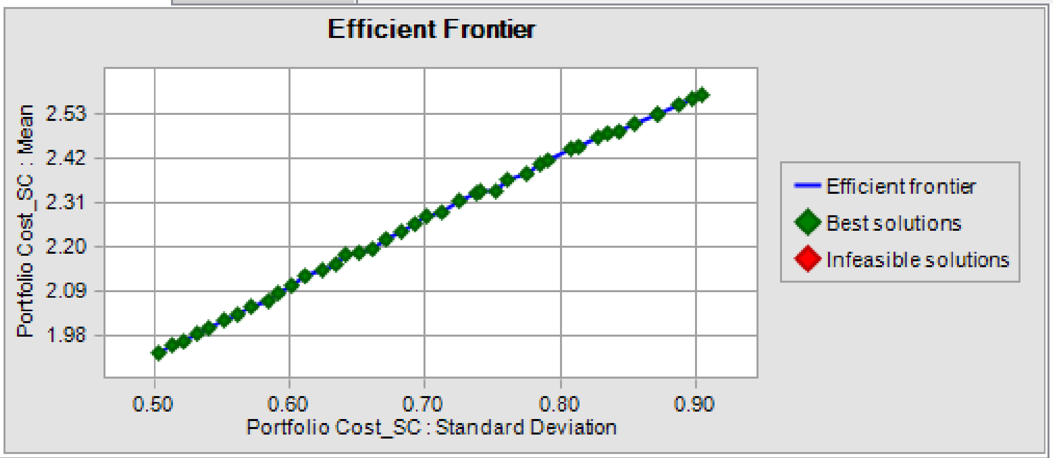
1000 Simulations Best Solution View

Efficient Frontier | Performance Chart



Best Solution: View test point: 0.50 Simulation # 256

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	1.94

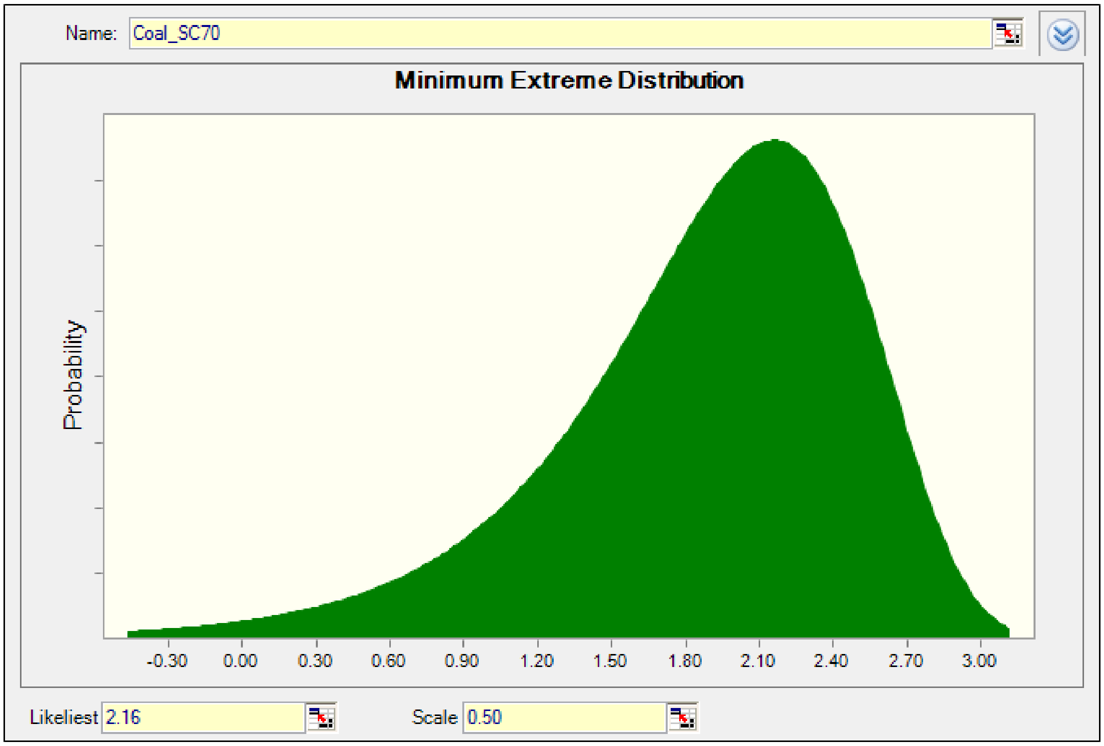
Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.50

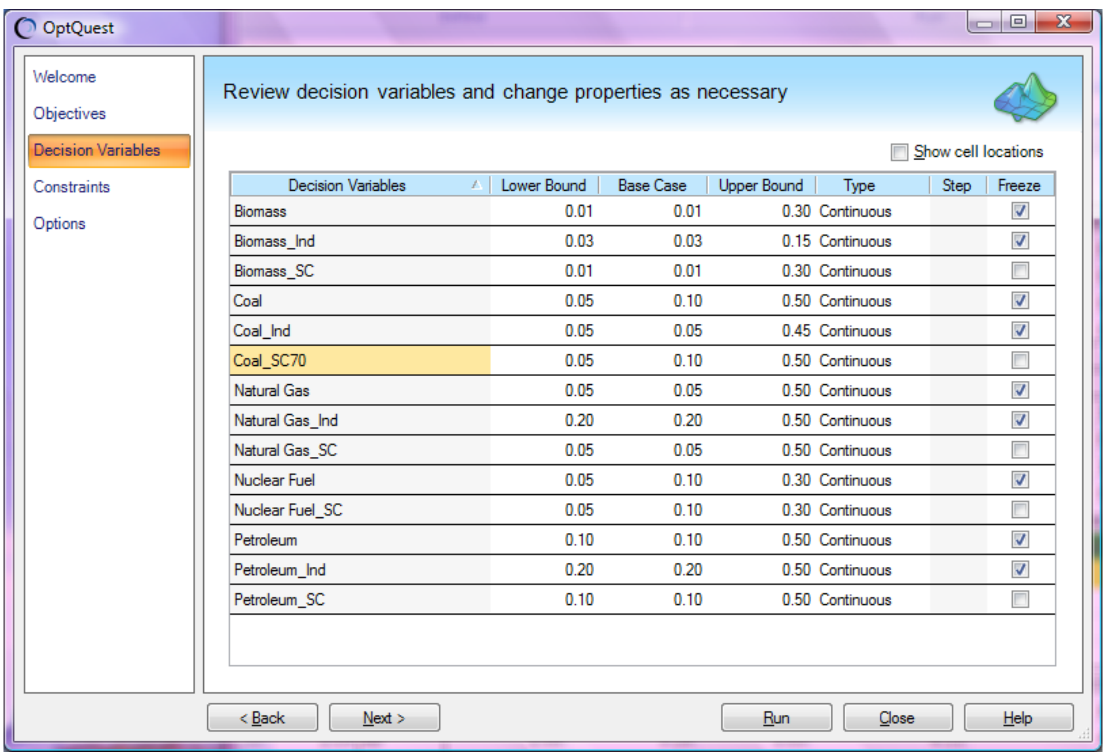
** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC50 + Natural Gas_SC + Nuclear Fuel_SC + Petr...	1.00	=	1.00

Decision Variables	Value
Biomass_SC	0.04
Coal_SC50	0.50
Natural Gas_SC	0.05
Nuclear Fuel_SC	0.30
Petroleum_SC	0.11

Scenario Five (Coal_SC70): With 70% Social Cost





Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC70	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐

OptQuest Results

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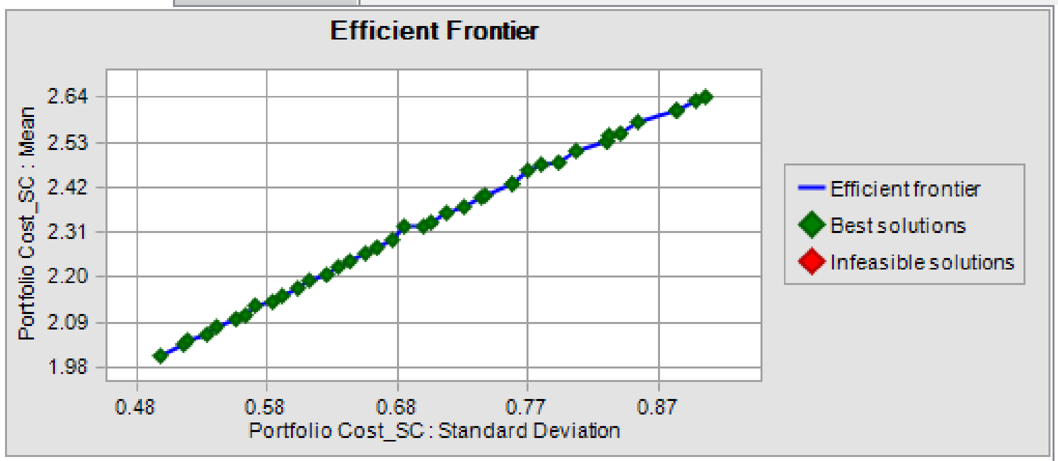
Best Solution View

Efficient Frontier | Performance Chart



Best Solution: View test point: 0.50 Simulation # 212

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	2.01

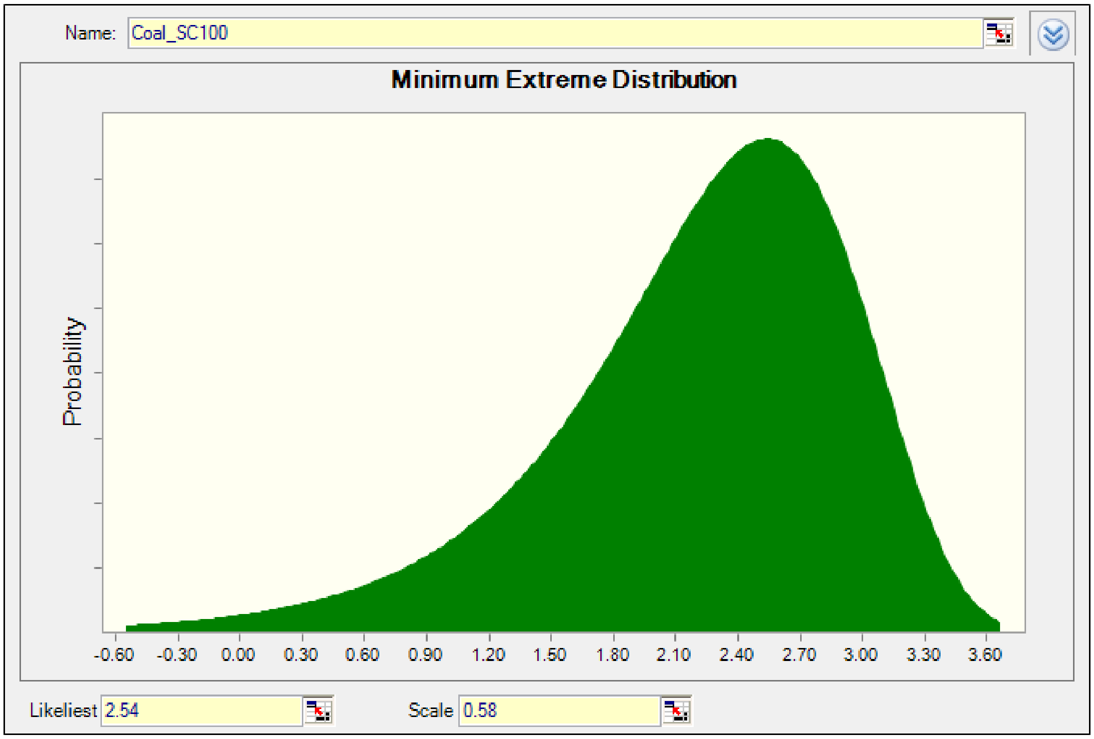
Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.50

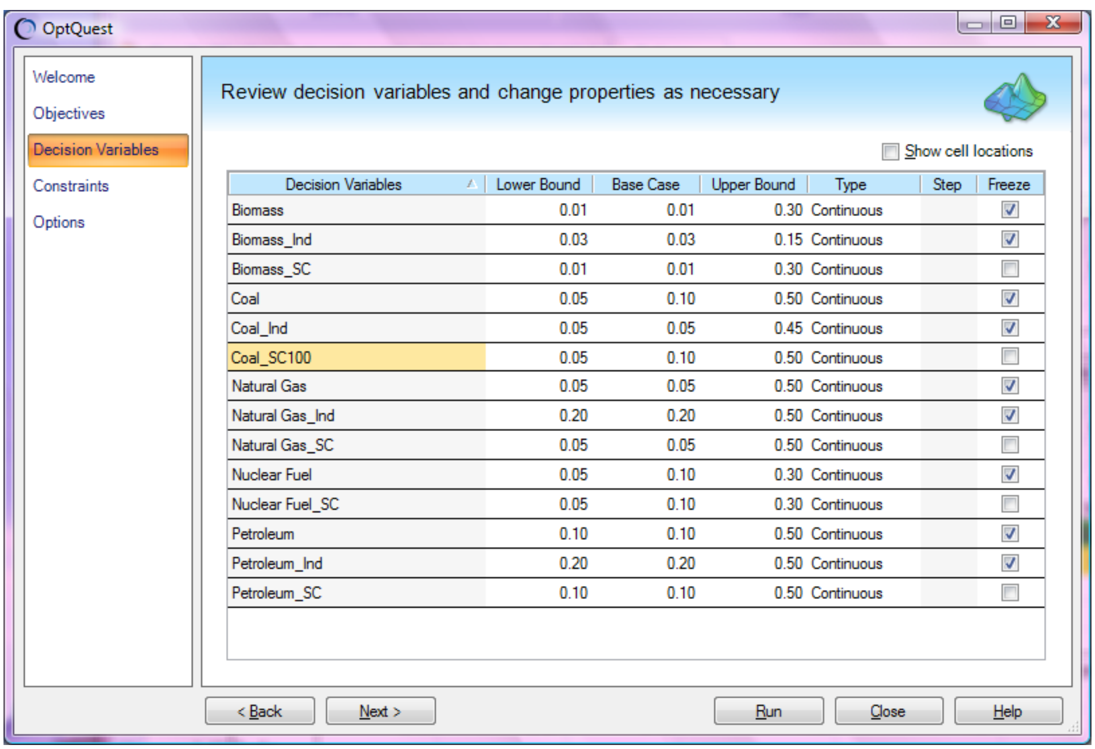
** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC70 + Natural Gas_SC + Nuclear Fuel_SC + Petr...	1.00	=	1.00

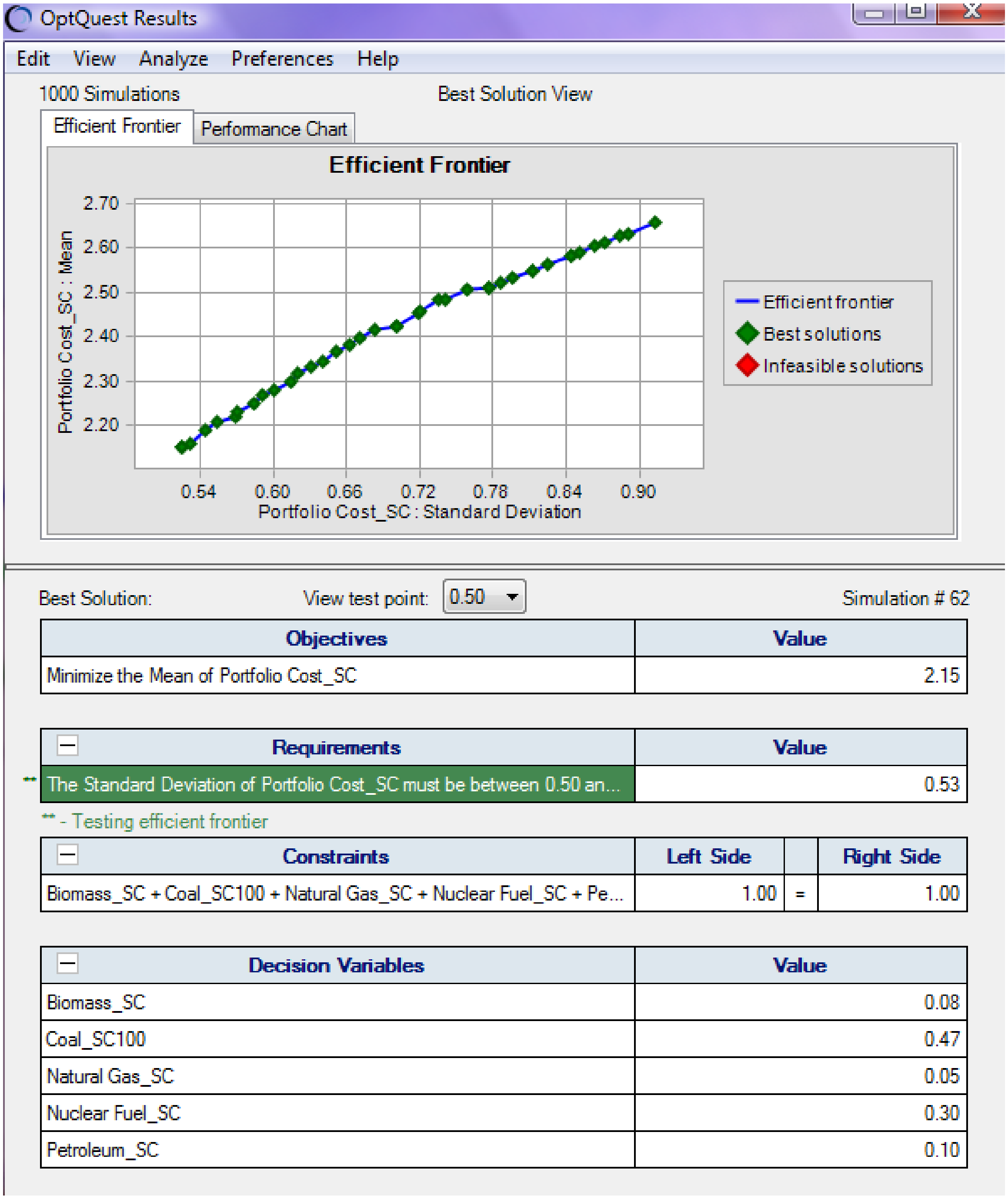
Decision Variables	Value
Biomass_SC	0.05
Coal_SC70	0.50
Natural Gas_SC	0.05
Nuclear Fuel_SC	0.30
Petroleum_SC	0.10

Scenario Six (Coal_SC100): With 100% Social Cost

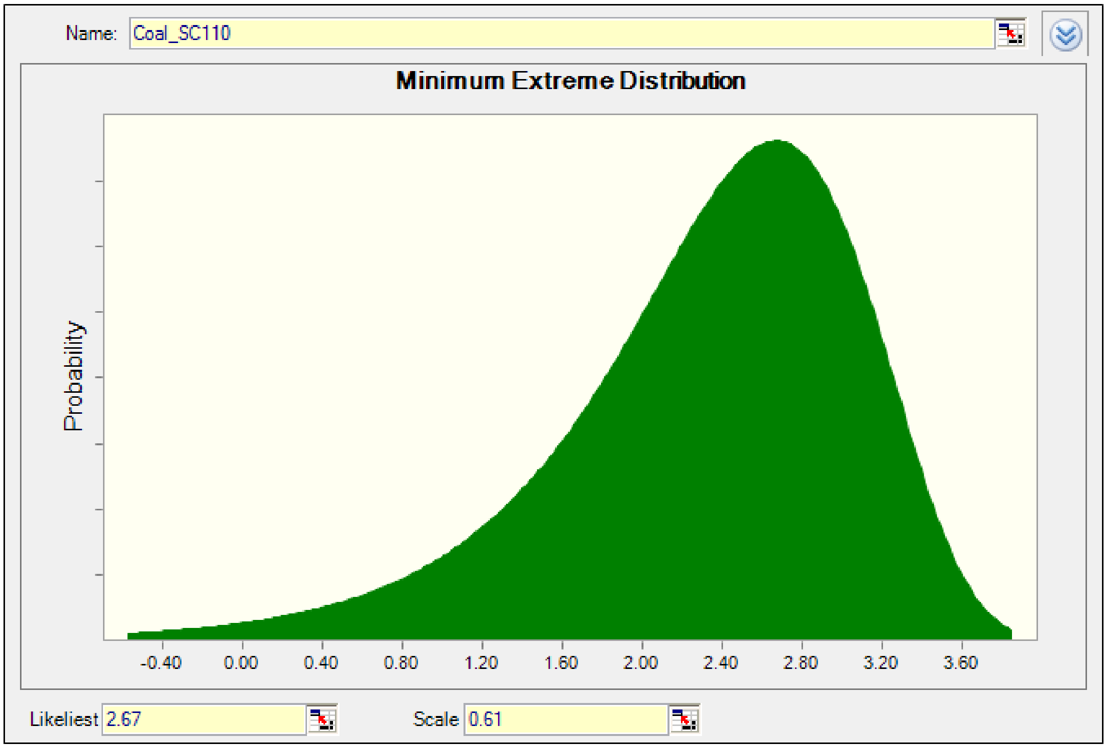


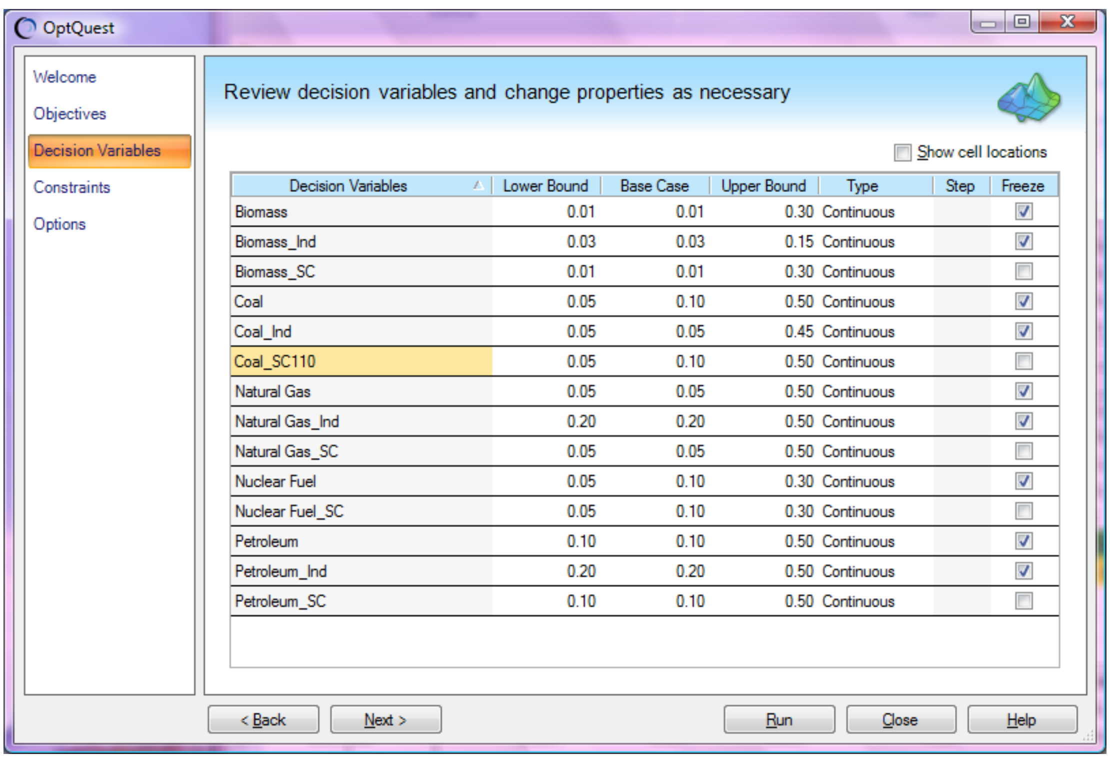


Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC100	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐

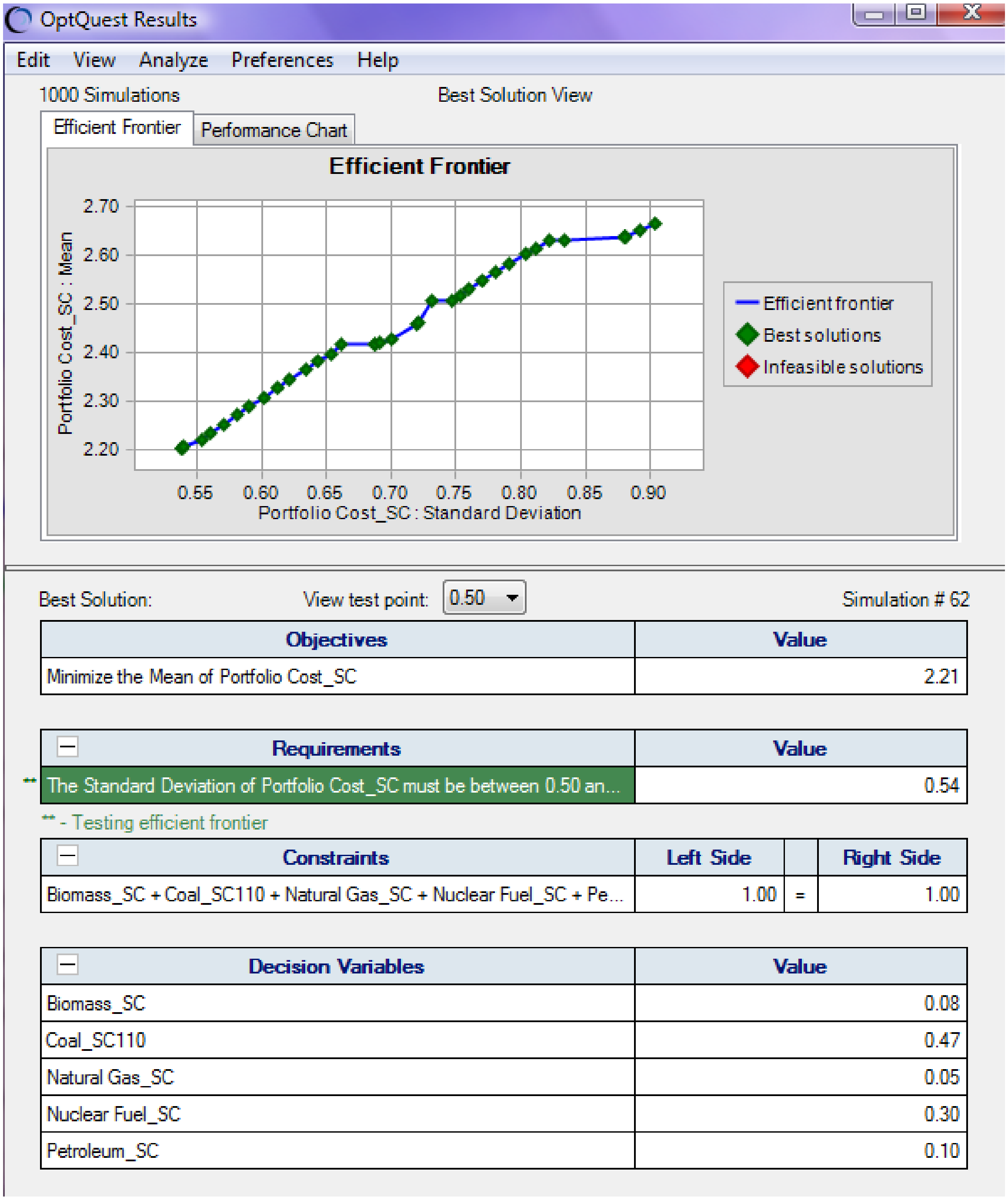

OptQuest Results
Edit View Analyze Preferences Help
1000 Simulations
Best Solution View
Efficient Frontier
Performance Chart
Efficient Frontier
2.70
2.60
2.50
2.40
2.30
2.20
Portfolio Cost_SC : Mean
0.54
0.60
0.66
0.72
0.78
0.84
0.90
Portfolio Cost_SC : Standard Deviation
Efficient frontier
Best solutions
Infeasible solutions
Best Solution:
View test point: 0.50
Simulation # 62
Objectives
Value
Minimize the Mean of Portfolio Cost_SC
2.15
Requirements
Value
The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...
0.53
** - Testing efficient frontier
Constraints
Left Side
Right Side
Biomass_SC + Coal_SC100 + Natural Gas_SC + Nuclear Fuel_SC + Pe...
1.00
=
1.00
Decision Variables
Value
Biomass_SC
0.08
Coal_SC100
0.47
Natural Gas_SC
0.05
Nuclear Fuel_SC
0.30
Petroleum_SC
0.10

Scenario Seven (Coal_SC110): With 110% Social Cost

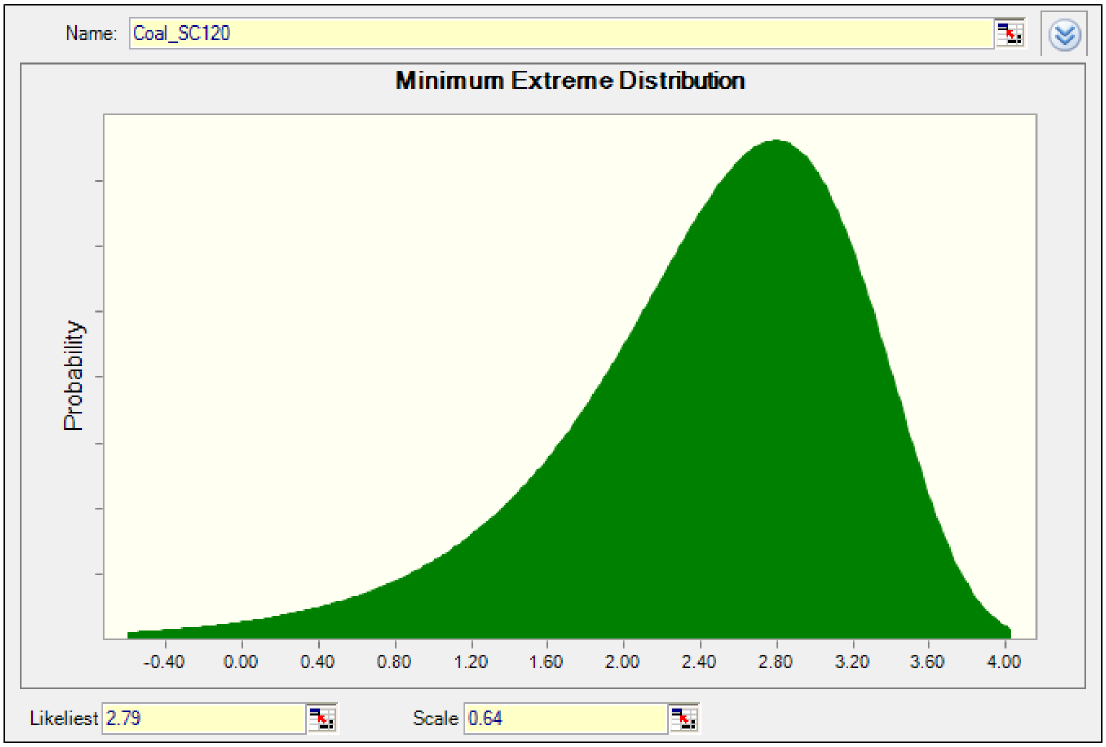


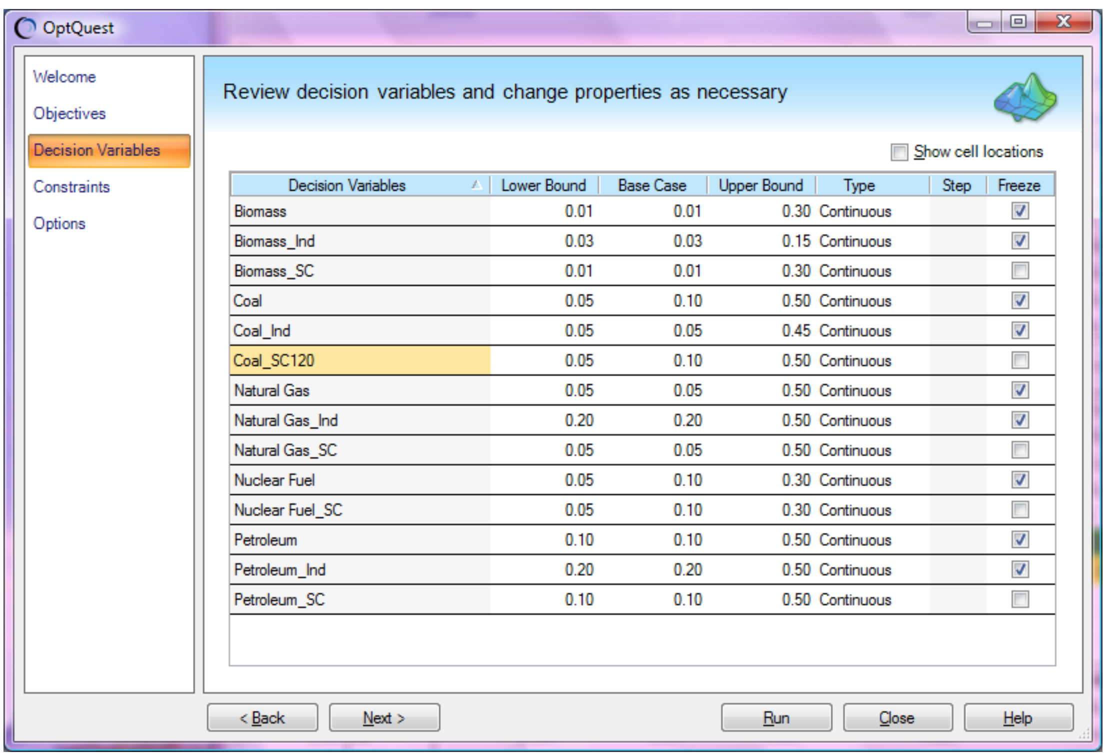


Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC110	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐


OptQuest Results
Edit View Analyze Preferences Help
1000 Simulations
Best Solution View
Efficient Frontier
Performance Chart
Efficient Frontier
Portfolio Cost_SC : Mean
2.70
2.60
2.50
2.40
2.30
2.20
0.55 0.60 0.65 0.70 0.75 0.80 0.85 0.90
Portfolio Cost_SC : Standard Deviation
Efficient frontier
Best solutions
Infeasible solutions
Best Solution:
View test point: 0.50
Simulation # 62
Objectives | Value
Minimize the Mean of Portfolio Cost_SC | 2.21
Requirements | Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an... | 0.54
** - Testing efficient frontier
Constraints | Left Side | | Right Side
Biomass_SC + Coal_SC110 + Natural Gas_SC + Nuclear Fuel_SC + Pe... | 1.00 | = | 1.00
Decision Variables | Value
Biomass_SC | 0.08
Coal_SC110 | 0.47
Natural Gas_SC | 0.05
Nuclear Fuel_SC | 0.30
Petroleum_SC | 0.10

Scenario Eight (Coal_SC120): With 120% Social Cost





Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC120	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐

OptQuest Results

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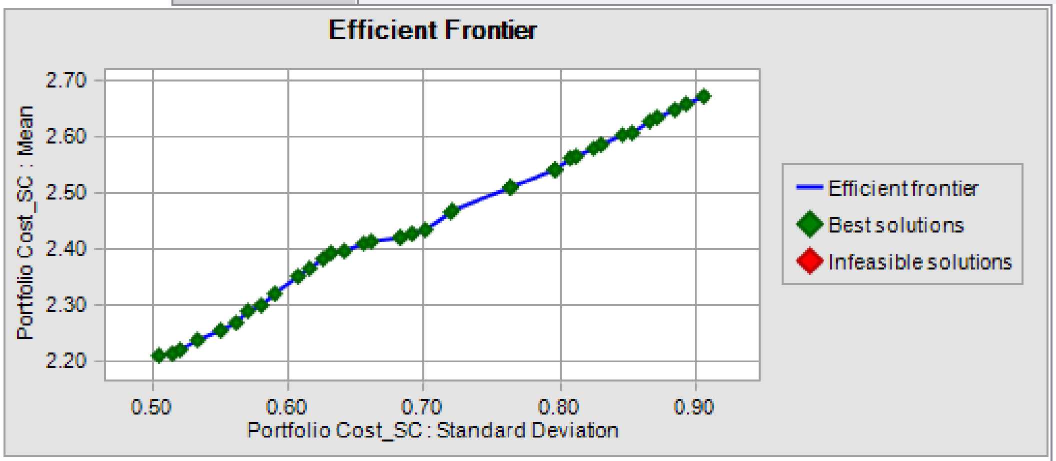
1000 Simulations — Best Solution View

Efficient Frontier | Performance Chart



Best Solution: View test point: 0.50 Simulation # 251

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	2.21

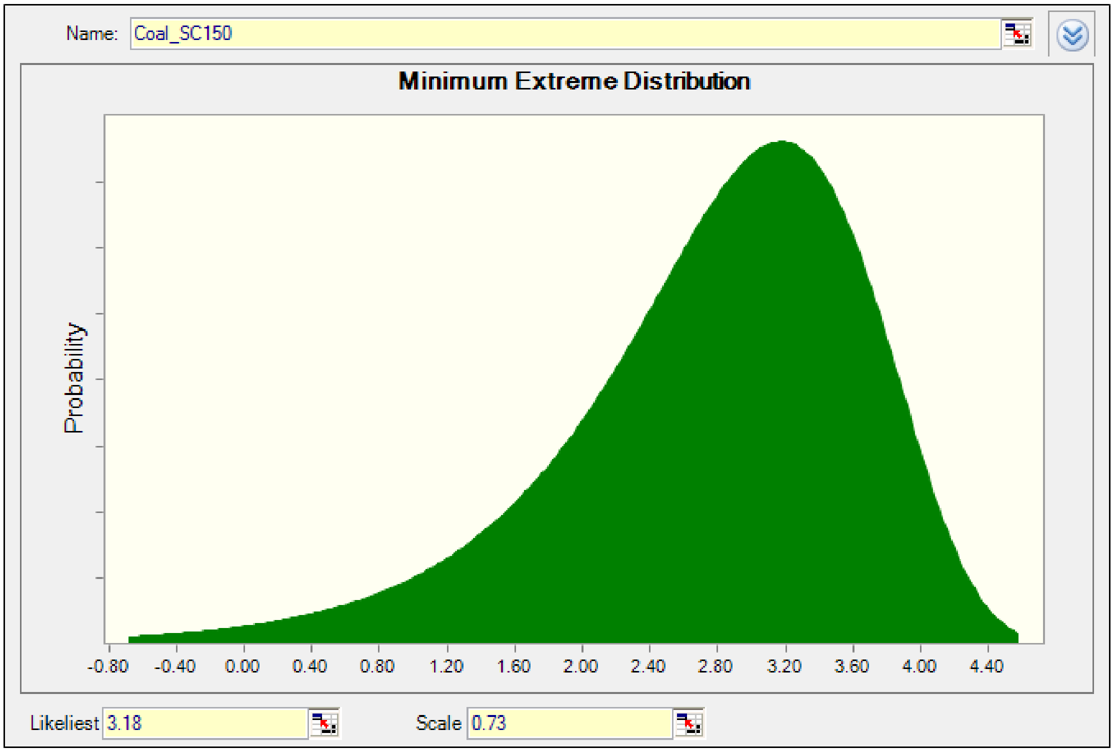
Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.51

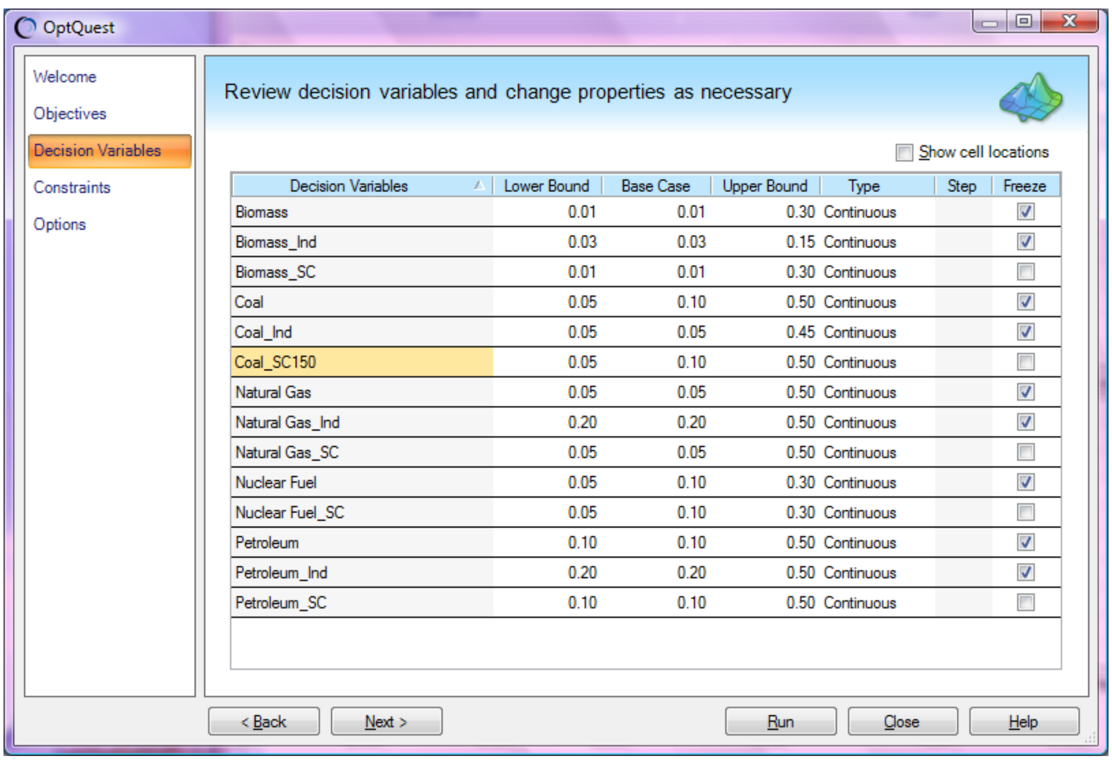
** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC120 + Natural Gas_SC + Nuclear Fuel_SC + Pe...	1.00	=	1.00

Decision Variables	Value
Biomass_SC	0.23
Coal_SC120	0.31
Natural Gas_SC	0.05
Nuclear Fuel_SC	0.30
Petroleum_SC	0.11

Scenario Nine (Coal_SC150): With 150% Social Cost





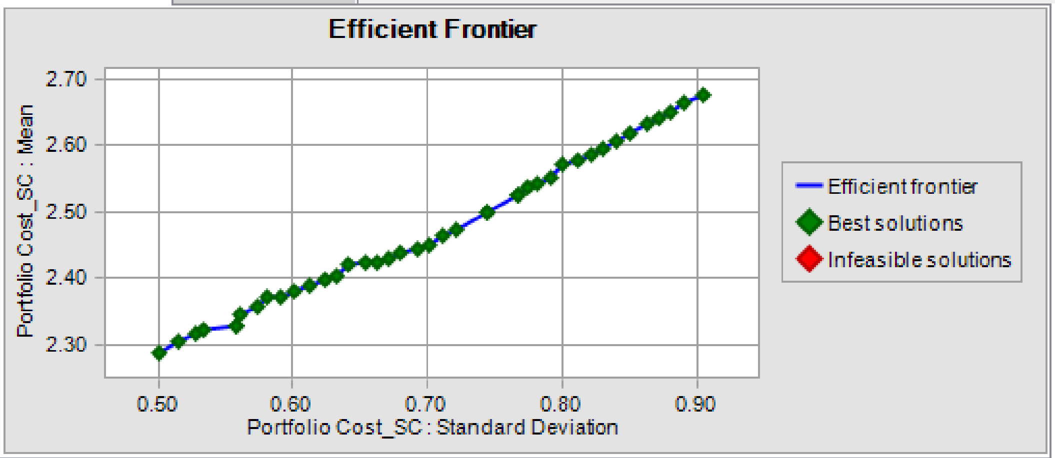
Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		✓
Biomass_Ind	0.03	0.03	0.15	Continuous		✓
Biomass_SC	0.01	0.01	0.30	Continuous		
Coal	0.05	0.10	0.50	Continuous		✓
Coal_Ind	0.05	0.05	0.45	Continuous		✓
Coal_SC150	0.05	0.10	0.50	Continuous		
Natural Gas	0.05	0.05	0.50	Continuous		✓
Natural Gas_Ind	0.20	0.20	0.50	Continuous		✓
Natural Gas_SC	0.05	0.05	0.50	Continuous		
Nuclear Fuel	0.05	0.10	0.30	Continuous		✓
Nuclear Fuel_SC	0.05	0.10	0.30	Continuous		
Petroleum	0.10	0.10	0.50	Continuous		✓
Petroleum_Ind	0.20	0.20	0.50	Continuous		✓
Petroleum_SC	0.10	0.10	0.50	Continuous		

OptQuest Results

Edit View Analyze Preferences Help

1000 Simulations   Best Solution View

Efficient Frontier | Performance Chart



Best Solution: View test point: 0.50   Simulation # 231

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	2.29

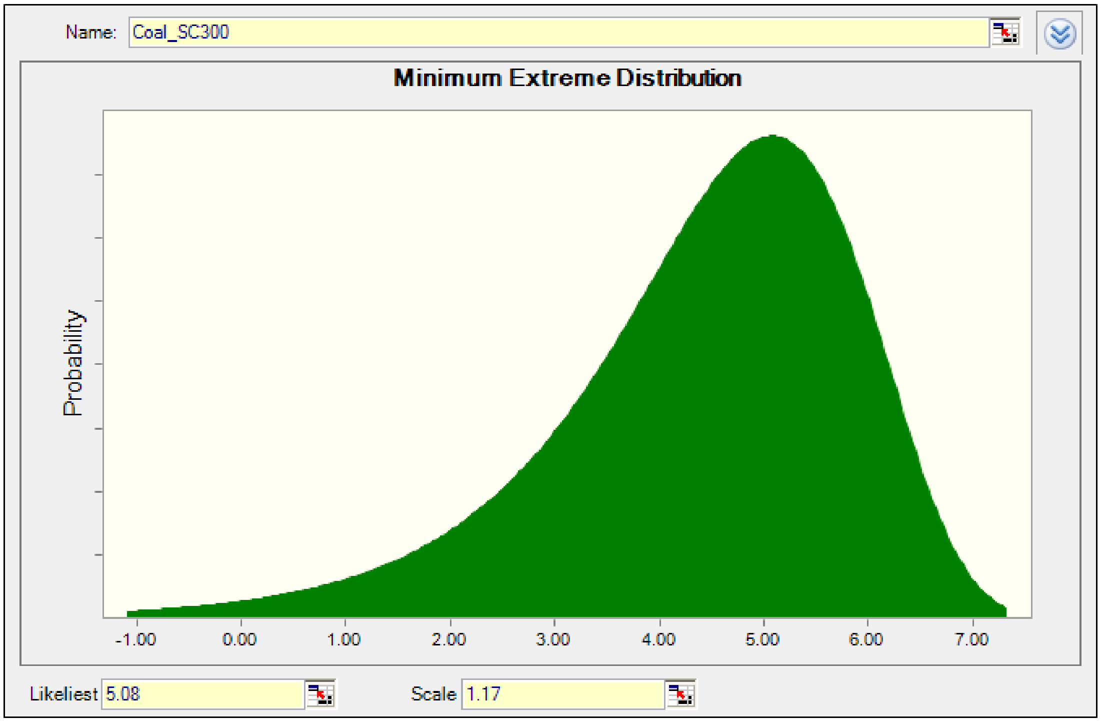
Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.50

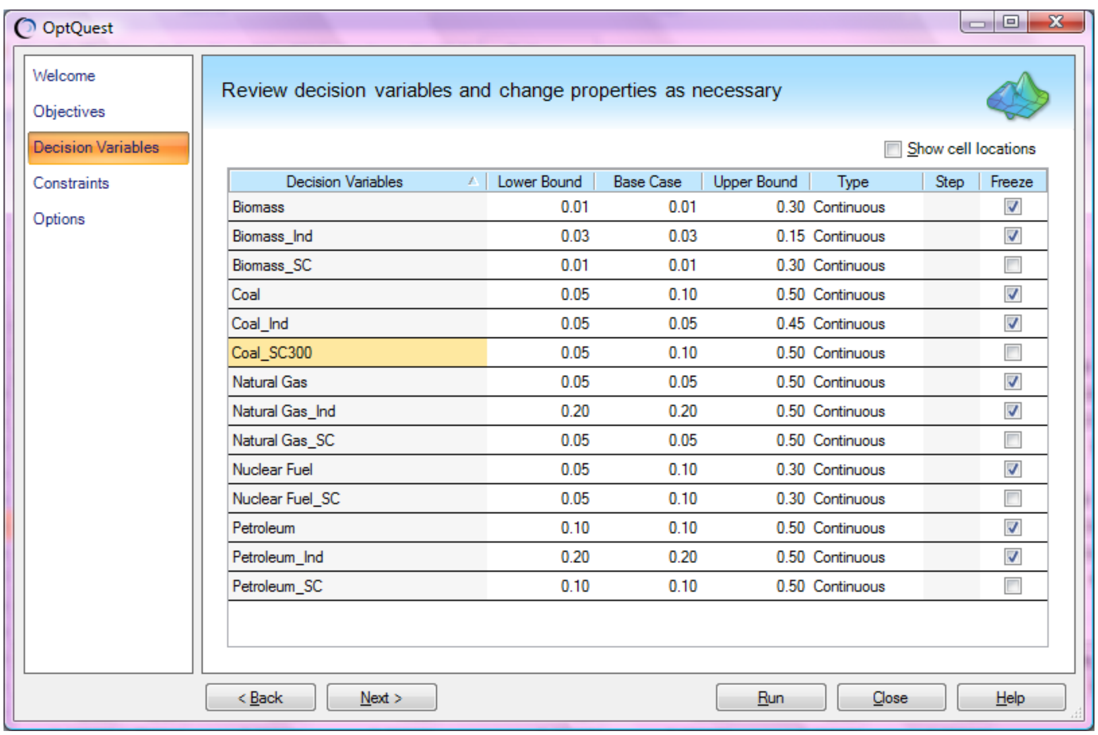
** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC150 + Natural Gas_SC + Nuclear Fuel_SC + Pe...	1.00	=	1.00

Decision Variables	Value
Biomass_SC	0.30
Coal_SC150	0.18
Natural Gas_SC	0.12
Nuclear Fuel_SC	0.30
Petroleum_SC	0.10

Scenario Ten (Coal_SC300): With 300% Social Cost





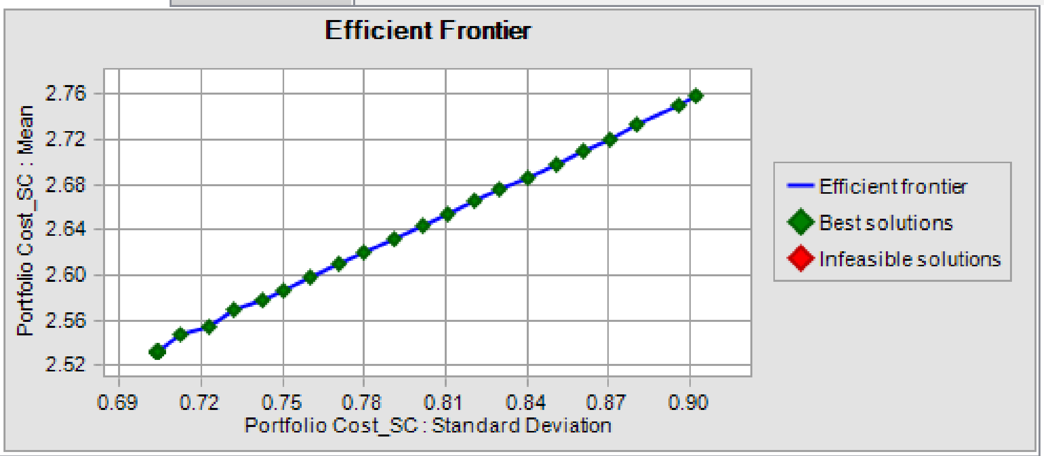
Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC300	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐

OptQuest Results

Edit View Analyze Preferences Help

1000 Simulations | Best Solution View

Efficient Frontier | Performance Chart



Best Solution: View test point: 0.50 Simulation # 56

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	2.53

Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.70

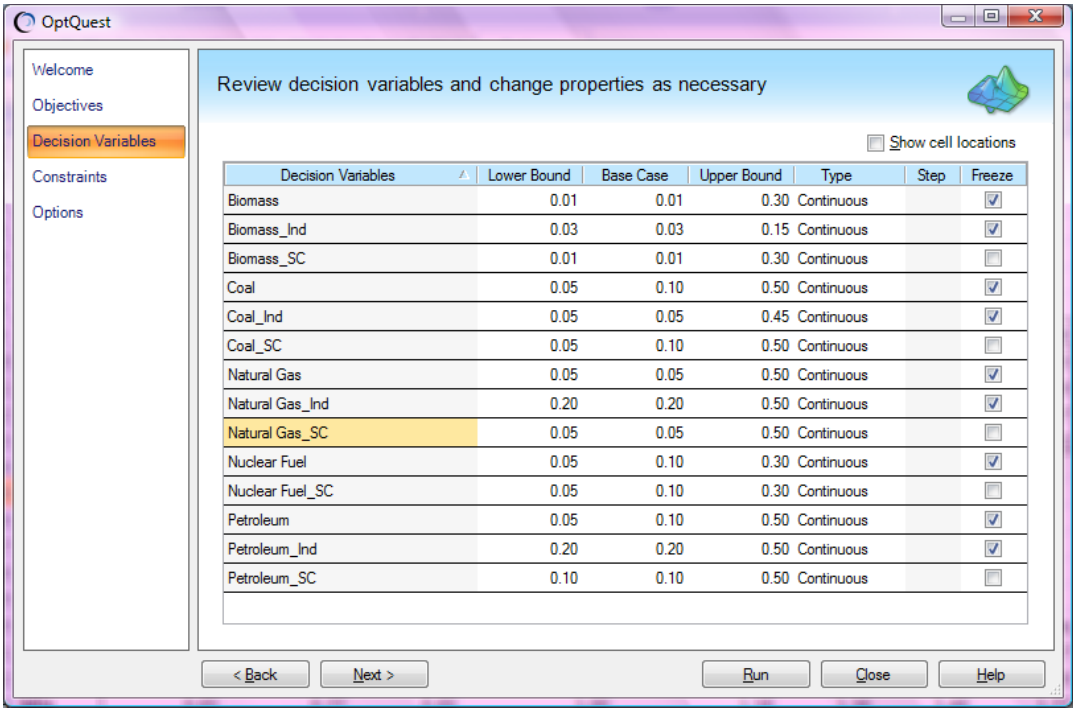
** - Testing efficient frontier

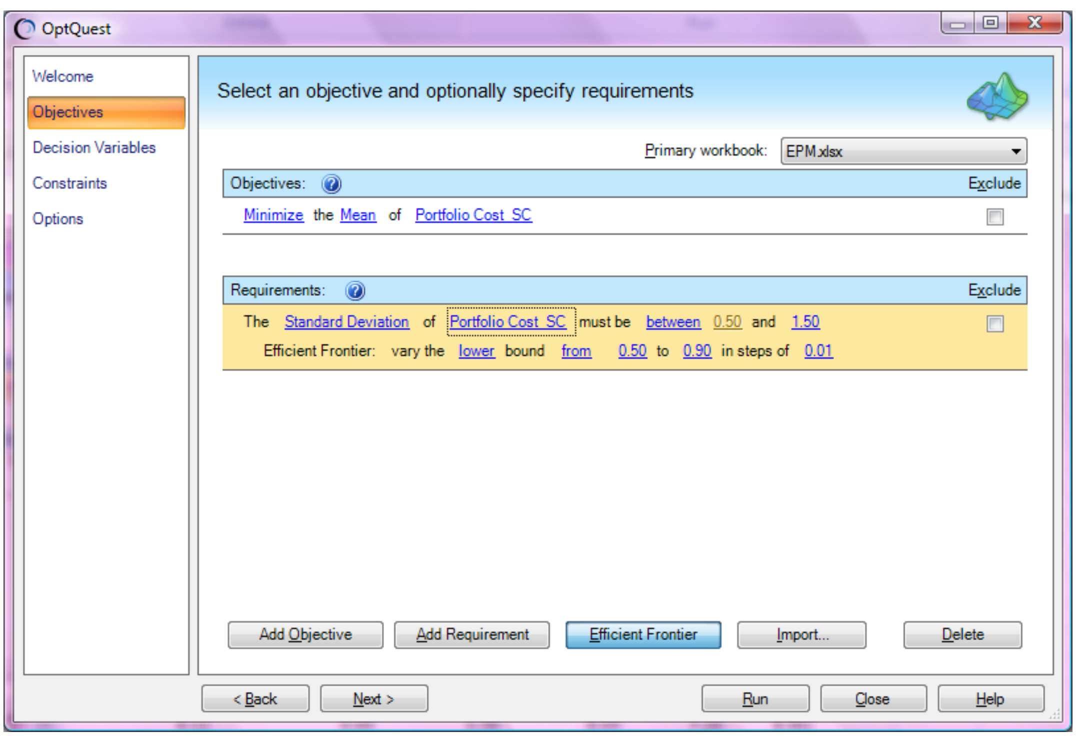
Constraints	Left Side		Right Side
Biomass_SC + Coal_SC300 + Natural Gas_SC + Nuclear Fuel_SC + Pe...	1.00	=	1.00

Decision Variables	Value
Biomass_SC	0.30
Coal_SC300	0.05
Natural Gas_SC	0.25
Nuclear Fuel_SC	0.30
Petroleum_SC	0.10

Appendix 8: EPM Scenario Simulation with Social Cost_ Natural Gas

Scenario One (Natural Gas_ SC): With no social cost added





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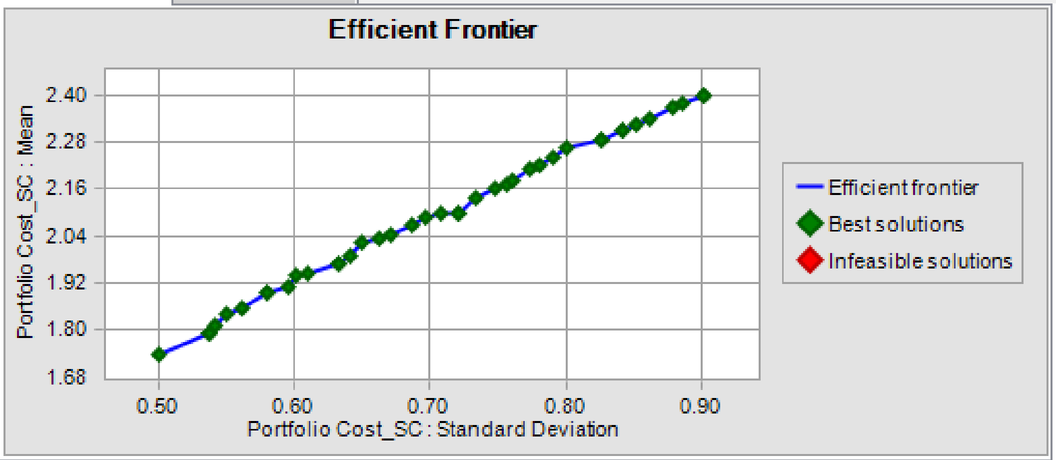


Best Solution: View test point: 0.50 Simulation # 523

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	1.74

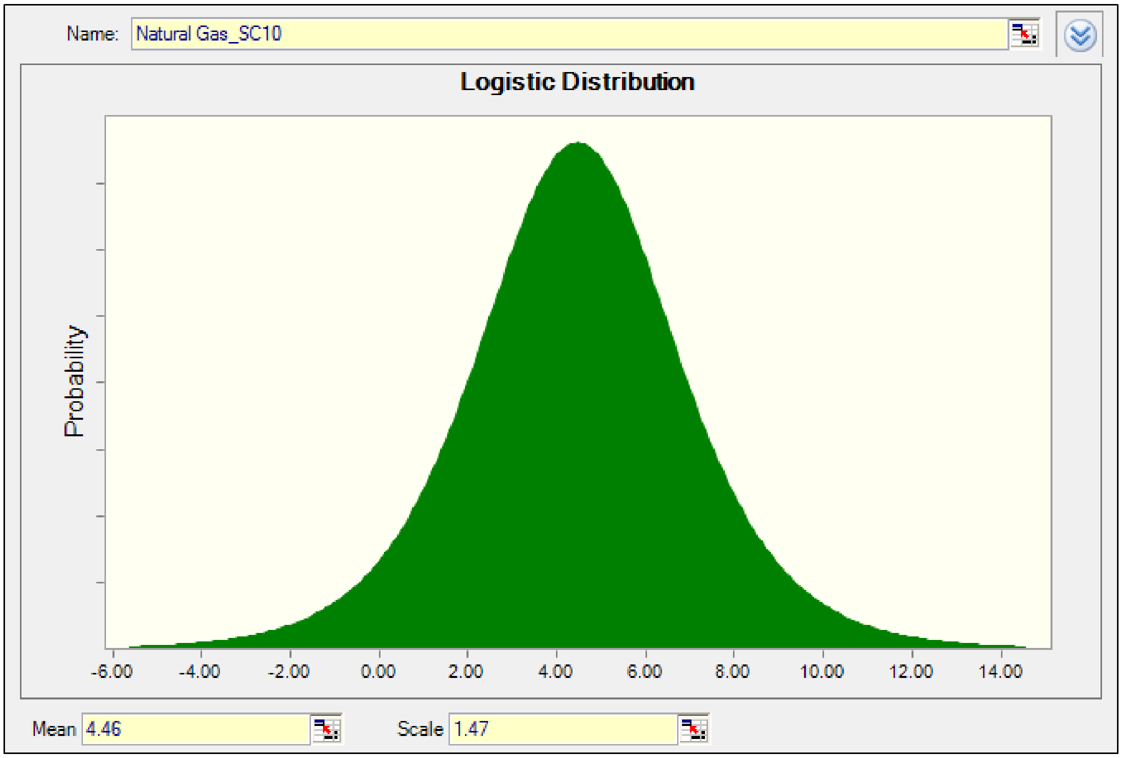
Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.50

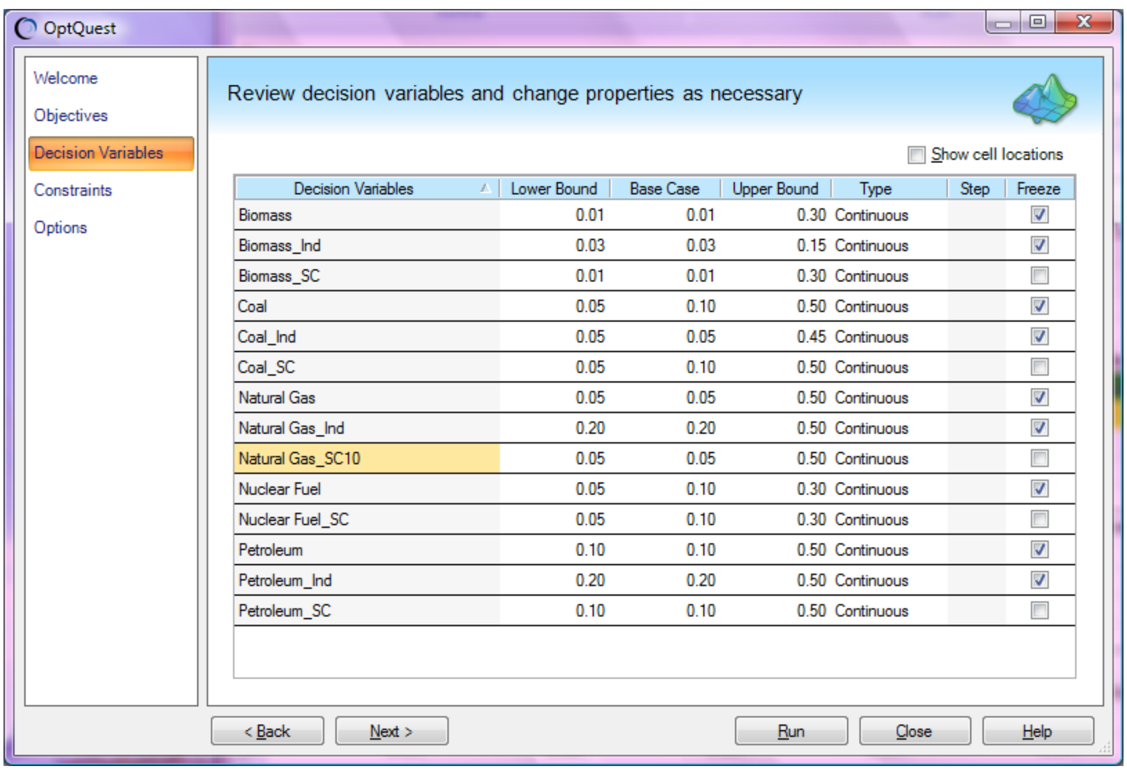
** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC + Natural Gas_SC + Nuclear Fuel_SC + Petrole...	1.00	=	1.00

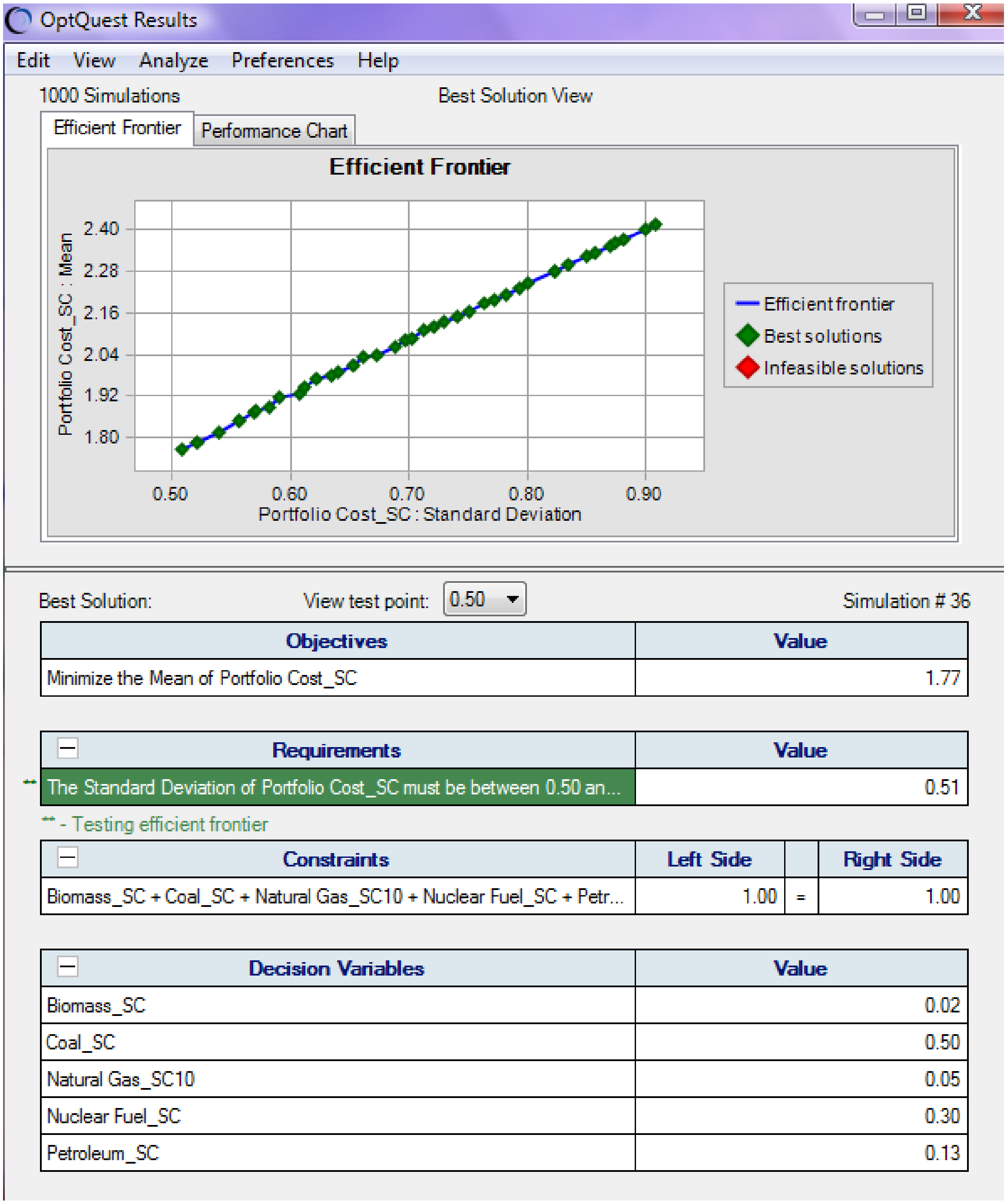
Decision Variables	Value
Biomass_SC	0.02
Coal_SC	0.50
Natural Gas_SC	0.05
Nuclear Fuel_SC	0.30
Petroleum_SC	0.13

Scenario Two (Natural Gas_ SC10): With 10% Social Cost





Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC10	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐


OptQuest Results
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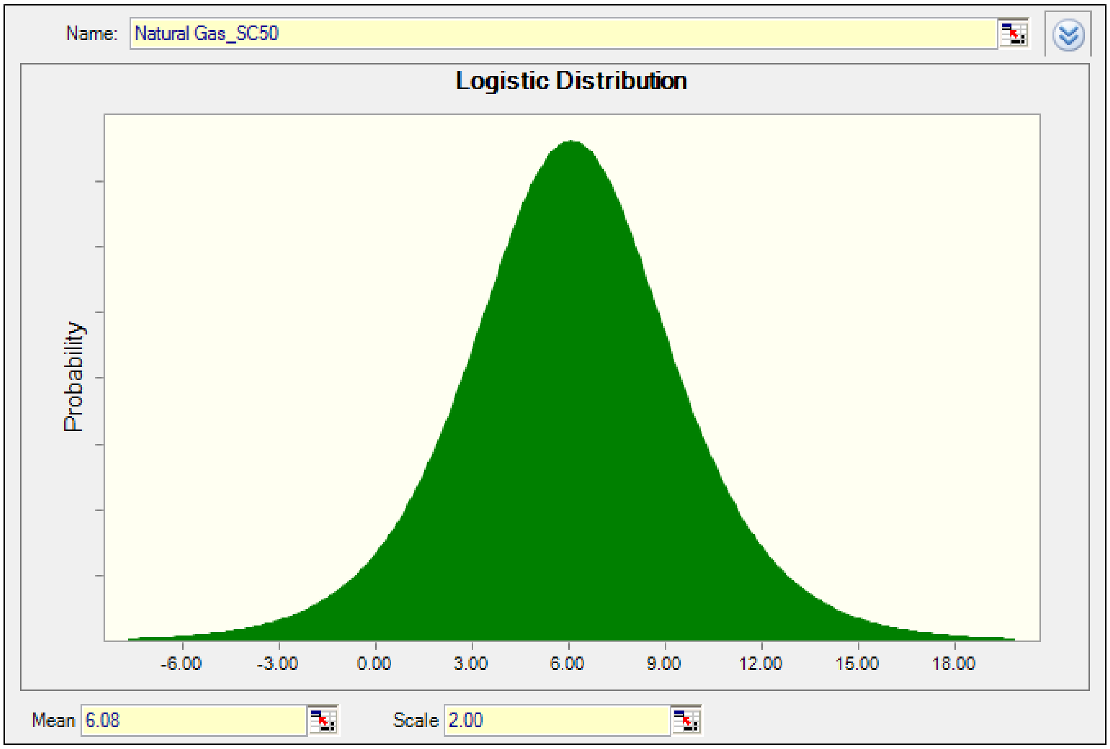
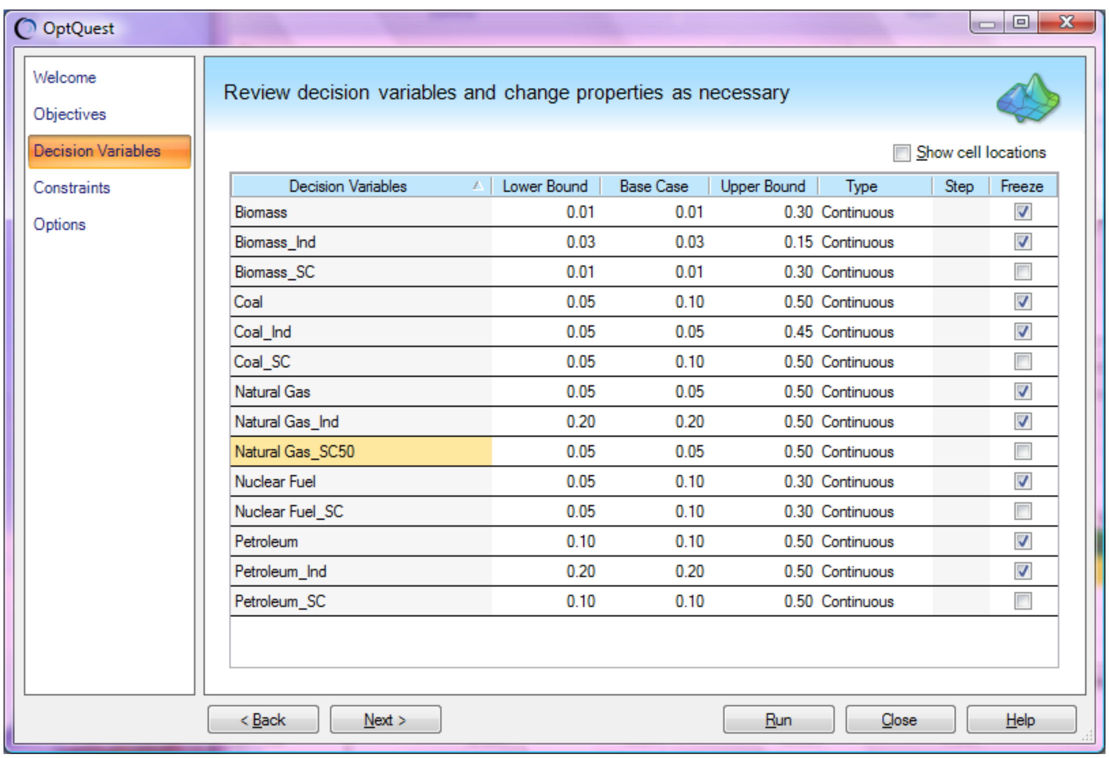
1000 Simulations
Best Solution View
Efficient Frontier
Performance Chart
Efficient Frontier
Portfolio Cost_SC : Mean
2.40
2.28
2.16
2.04
1.92
1.80
0.50
0.60
0.70
0.80
0.90
Portfolio Cost_SC : Standard Deviation
Efficient frontier
Best solutions
Infeasible solutions
Best Solution:
View test point: 0.50
Simulation # 36
Objectives | Value
Minimize the Mean of Portfolio Cost_SC | 1.77
Requirements | Value
The Standard Deviation of Portfolio Cost_SC must be between 0.50 an... | 0.51
** - Testing efficient frontier
Constraints | Left Side | | Right Side
Biomass_SC + Coal_SC + Natural Gas_SC10 + Nuclear Fuel_SC + Petr... | 1.00 | = | 1.00
Decision Variables | Value
Biomass_SC | 0.02
Coal_SC | 0.50
Natural Gas_SC10 | 0.05
Nuclear Fuel_SC | 0.30
Petroleum_SC | 0.13

Scenario Three (Natural Gas_ SC50): With 50% Social Cost





Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC50	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐

OptQuest Results

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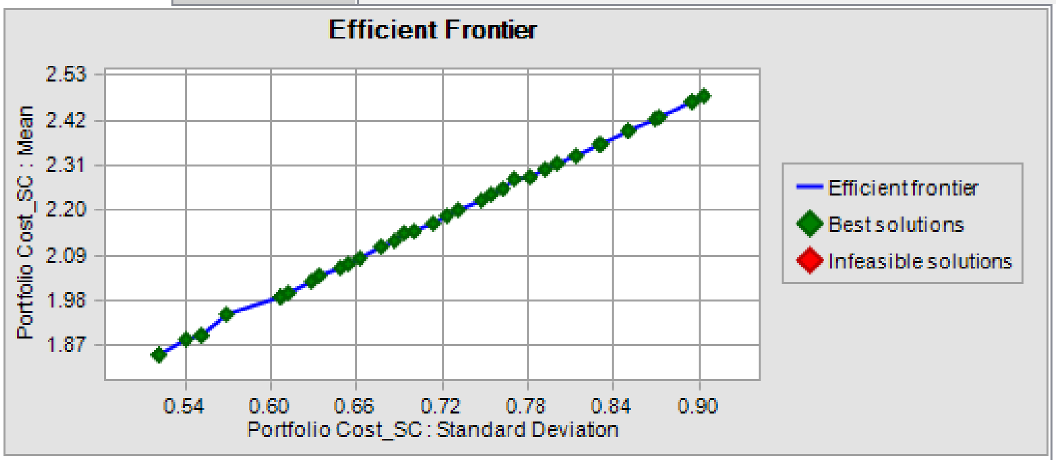
Efficient Frontier | Performance Chart



Best Solution: View test point: 0.50 Simulation # 112

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	1.85

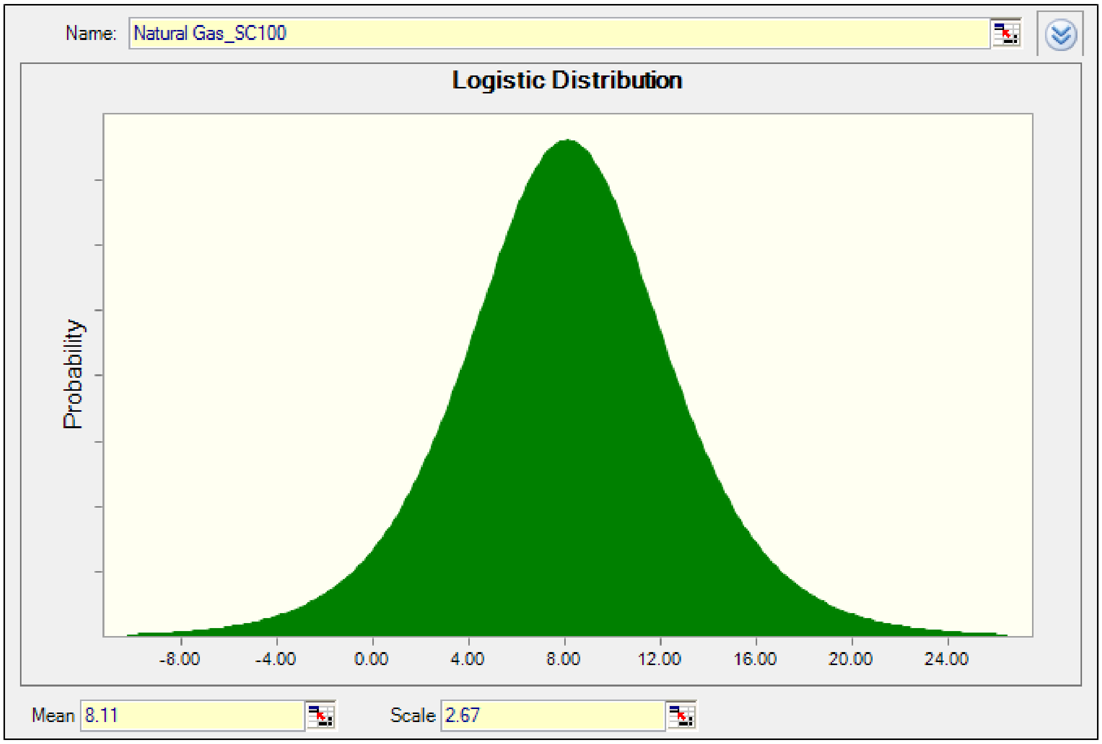
Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.52

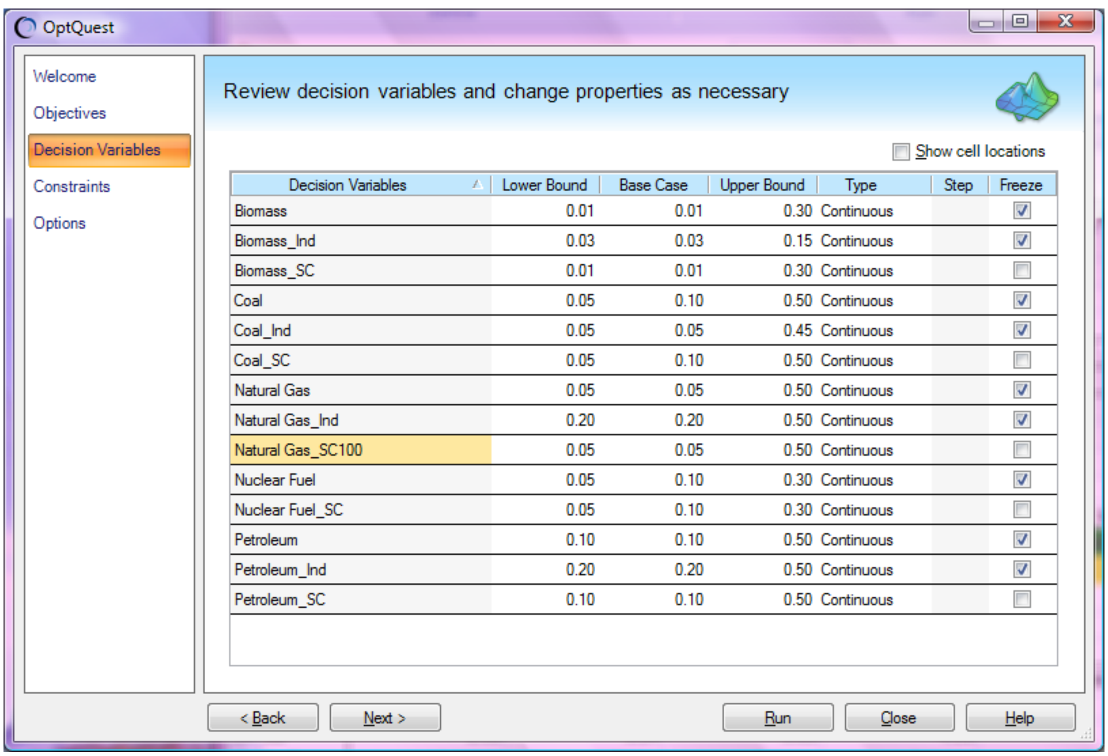
** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC + Natural Gas_SC50 + Nuclear Fuel_SC + Petr...	1.00	=	1.00

Decision Variables	Value
Biomass_SC	0.02
Coal_SC	0.50
Natural Gas_SC50	0.05
Nuclear Fuel_SC	0.30
Petroleum_SC	0.13

Scenario Four (Natural Gas_ SC100): With 100% Social Cost





Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC100	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐

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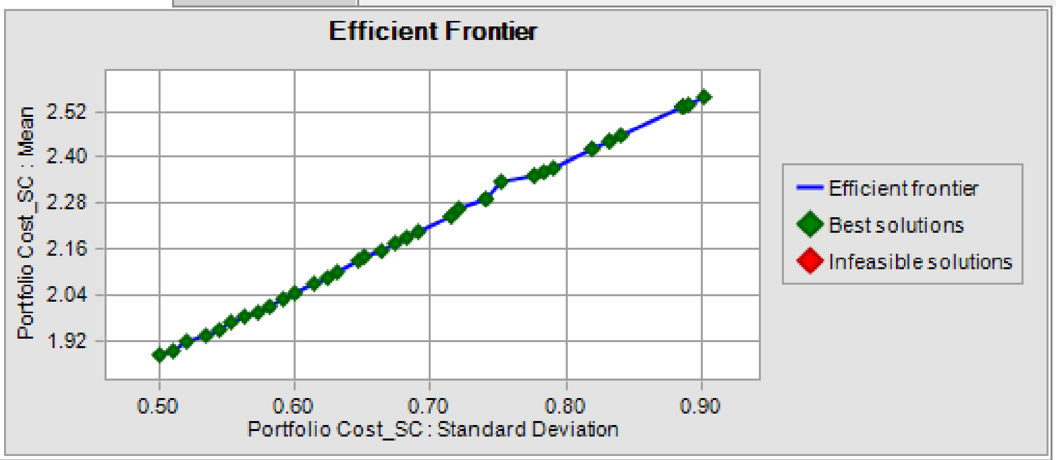


Best Solution: View test point: 0.50 Simulation # 268

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	1.89

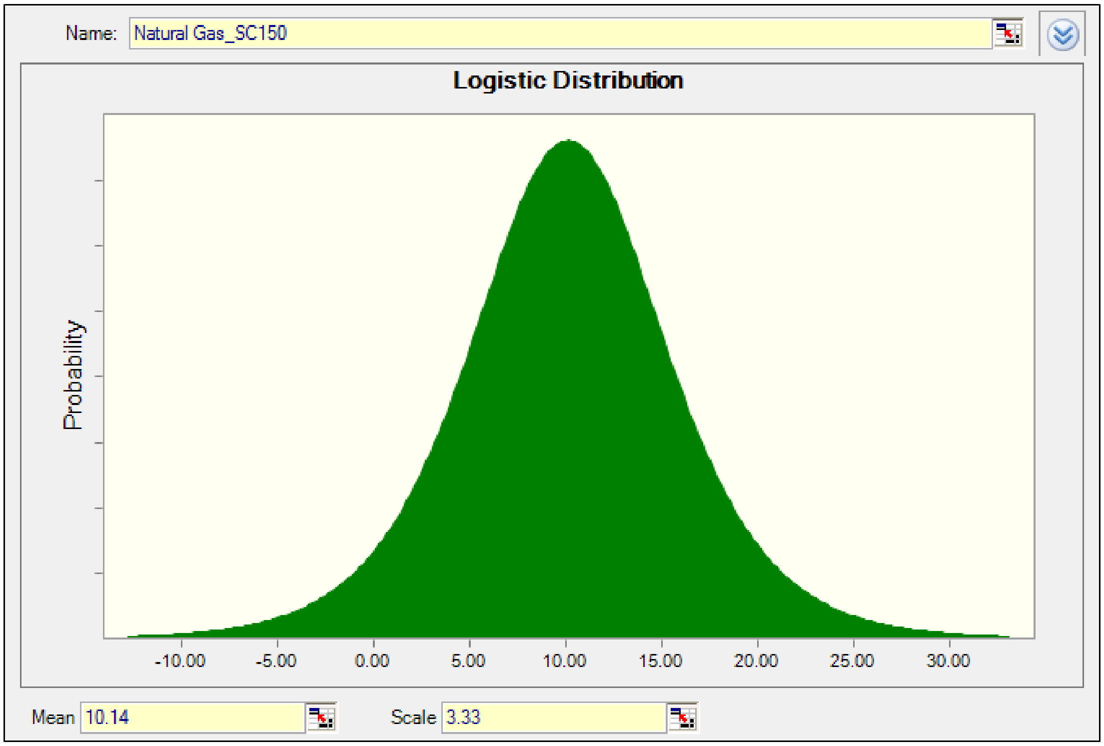
Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.50

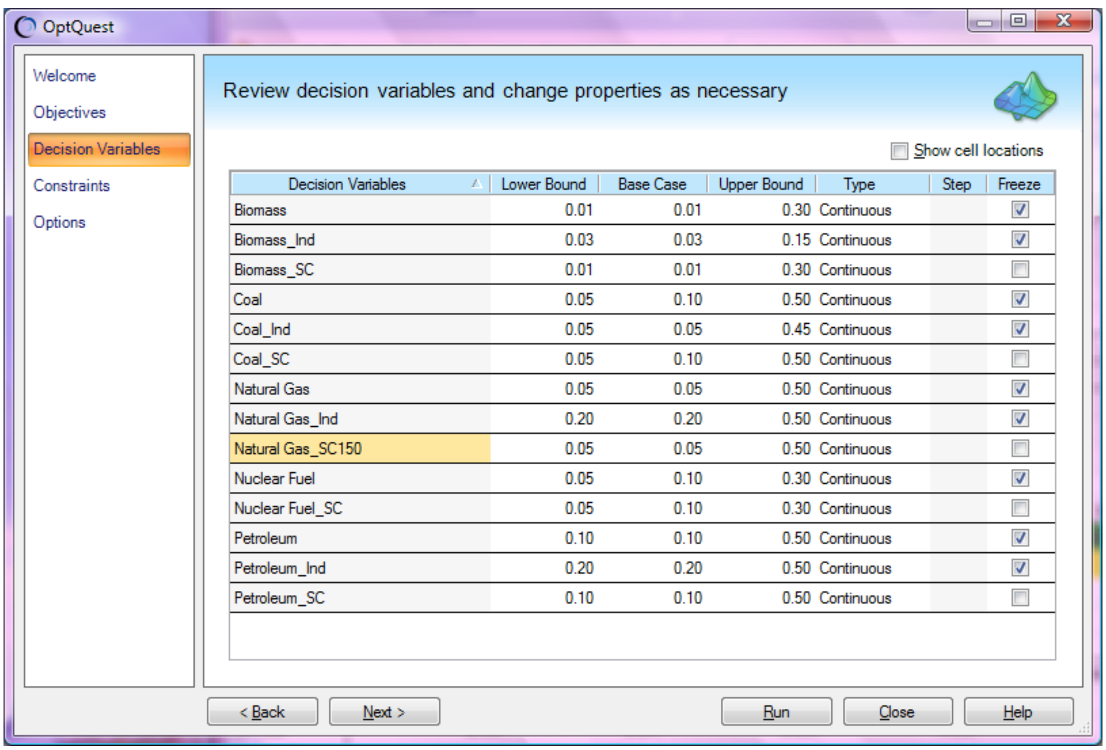
** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC + Natural Gas_SC100 + Nuclear Fuel_SC + Pe...	1.00	=	1.00

Decision Variables	Value
Biomass_SC	0.04
Coal_SC	0.50
Natural Gas_SC100	0.05
Nuclear Fuel_SC	0.30
Petroleum_SC	0.11

Scenario Five (Natural Gas_ SC150): With 150% Social Cost





Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC	0.05	0.10	0.50	Continuous		
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC150	0.05	0.05	0.50	Continuous		
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC	0.05	0.10	0.30	Continuous		
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		

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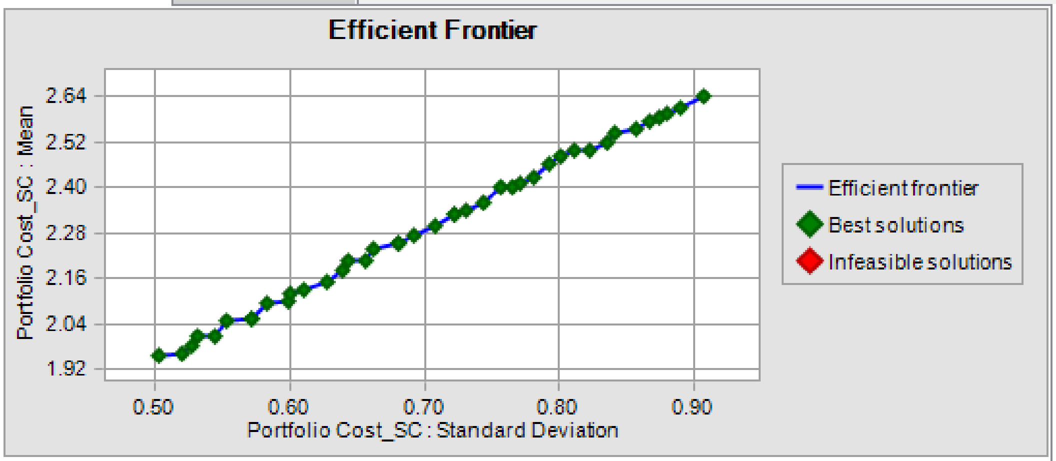


Best Solution: View test point: 0.50 Simulation # 614

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	1.96

Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.50

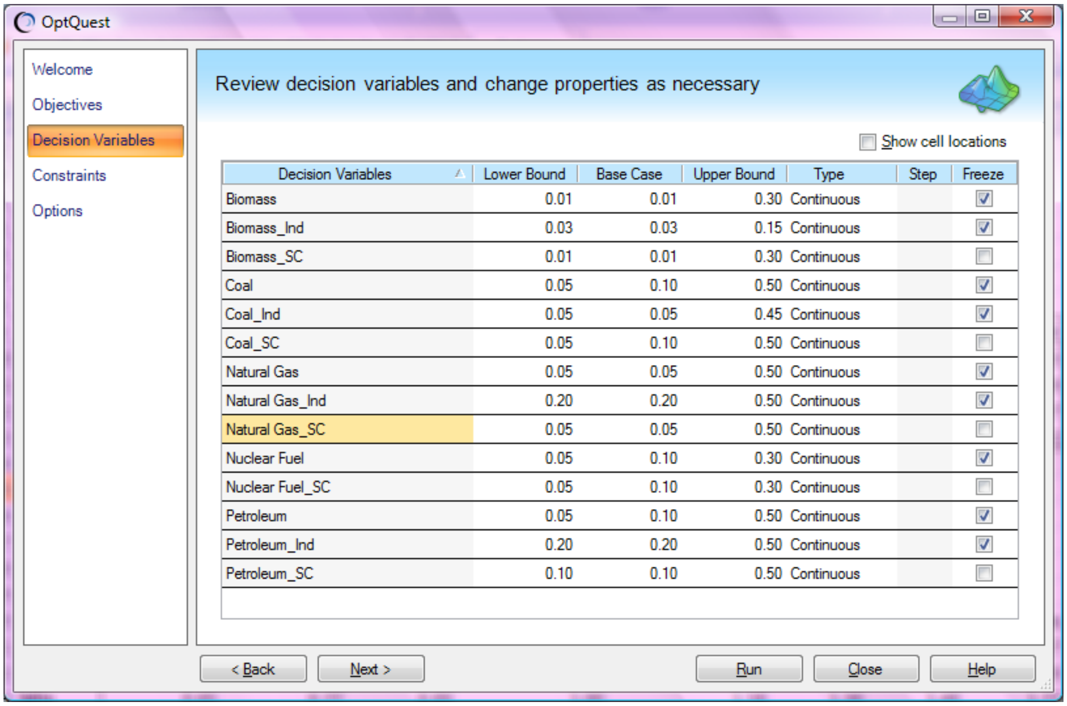
** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC + Natural Gas_SC150 + Nuclear Fuel_SC + Pe...	1.00	=	1.00

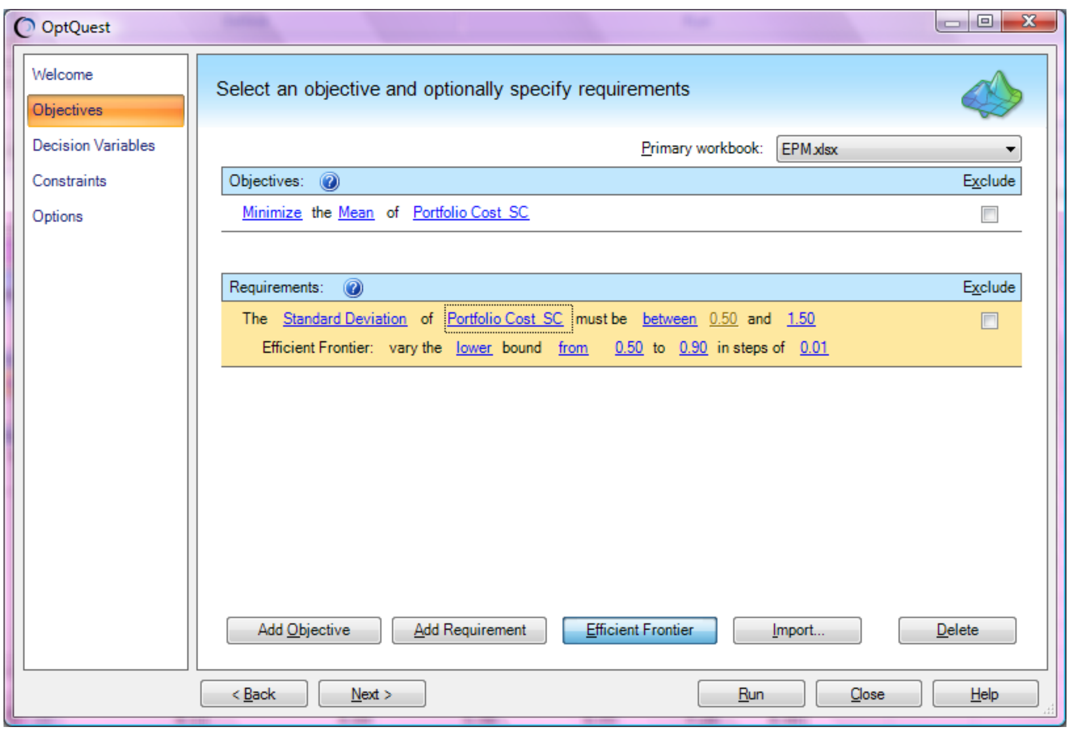
Decision Variables	Value
Biomass_SC	0.07
Coal_SC	0.50
Natural Gas_SC150	0.05
Nuclear Fuel_SC	0.28
Petroleum_SC	0.10

Appendix 9: EPM Scenario Simulation with Social Cost_ Nuclear Fuel

Scenario One (Nuclear Fuel_ SC): With no social cost added



Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC	0.05	0.10	0.30	Continuous		☐
Petroleum	0.05	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐



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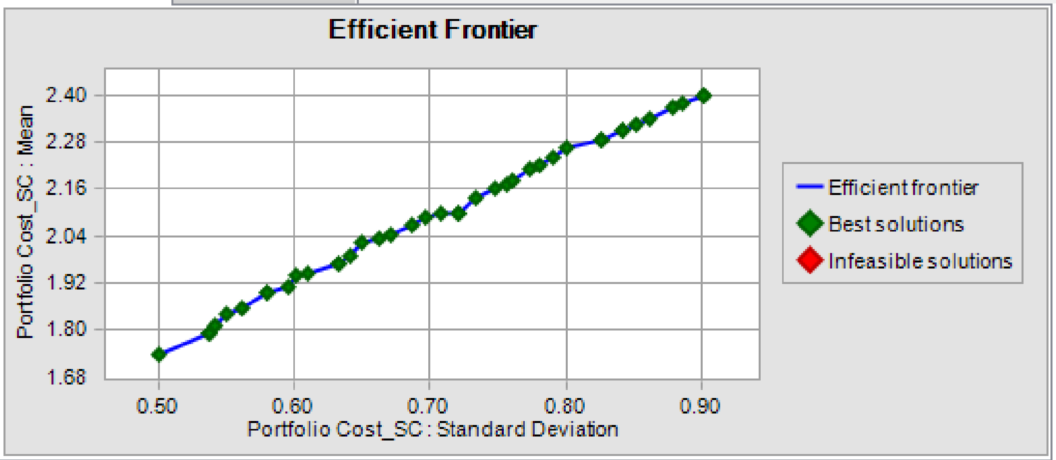


Best Solution: View test point: 0.50 Simulation # 523

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	1.74

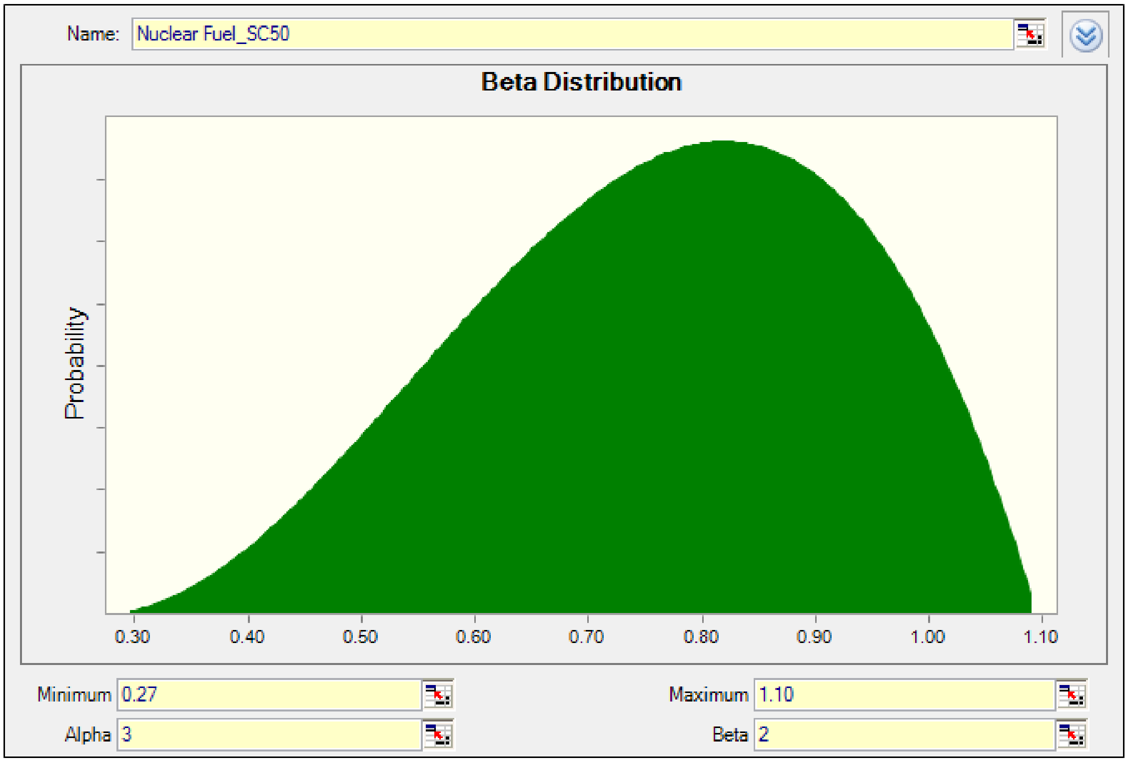
Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.50

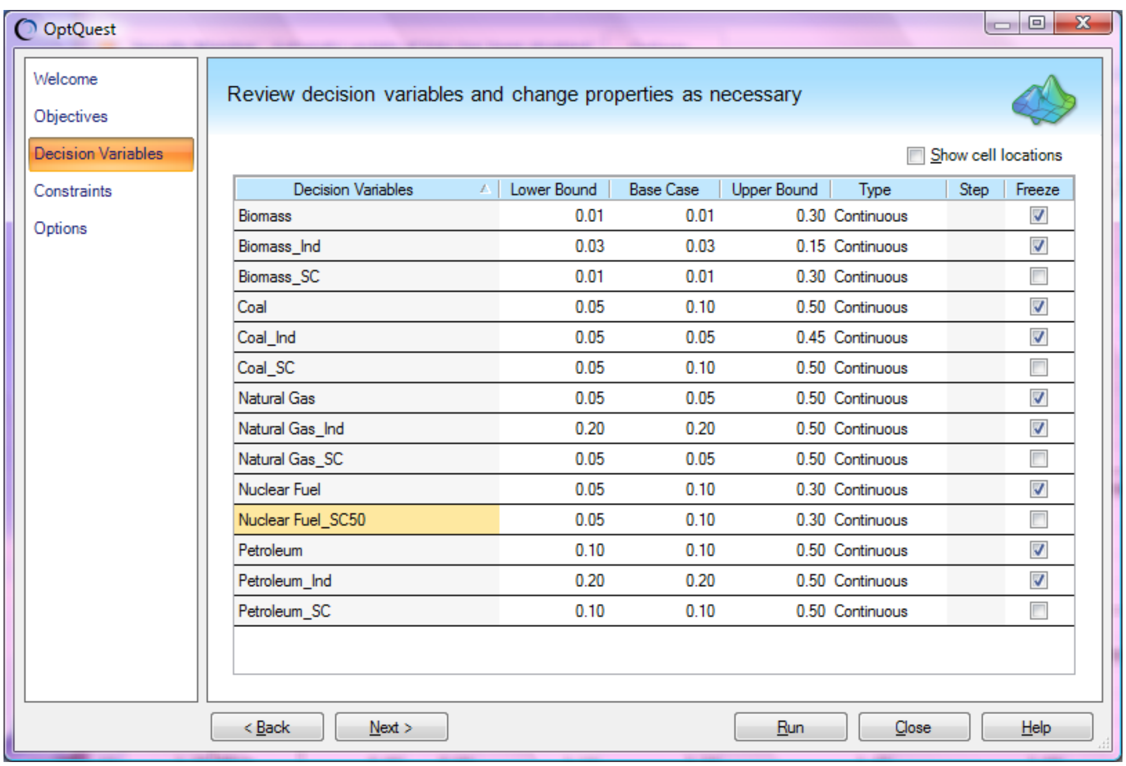
** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC + Natural Gas_SC + Nuclear Fuel_SC + Petrole...	1.00	=	1.00

Decision Variables	Value
Biomass_SC	0.02
Coal_SC	0.50
Natural Gas_SC	0.05
Nuclear Fuel_SC	0.30
Petroleum_SC	0.13

Scenario Two (Nuclear Fuel_ SC50): With 50% Social Cost





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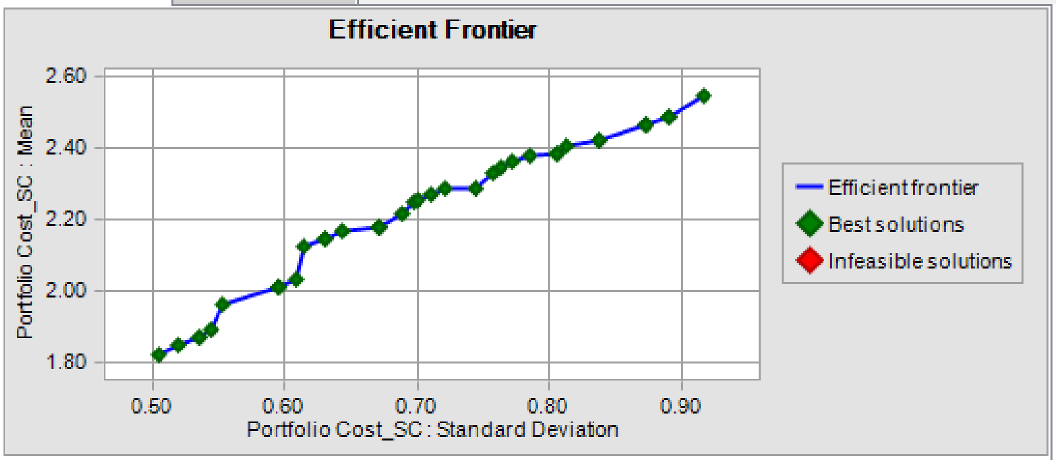


Best Solution: View test point: 0.50 Simulation # 29

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	1.82

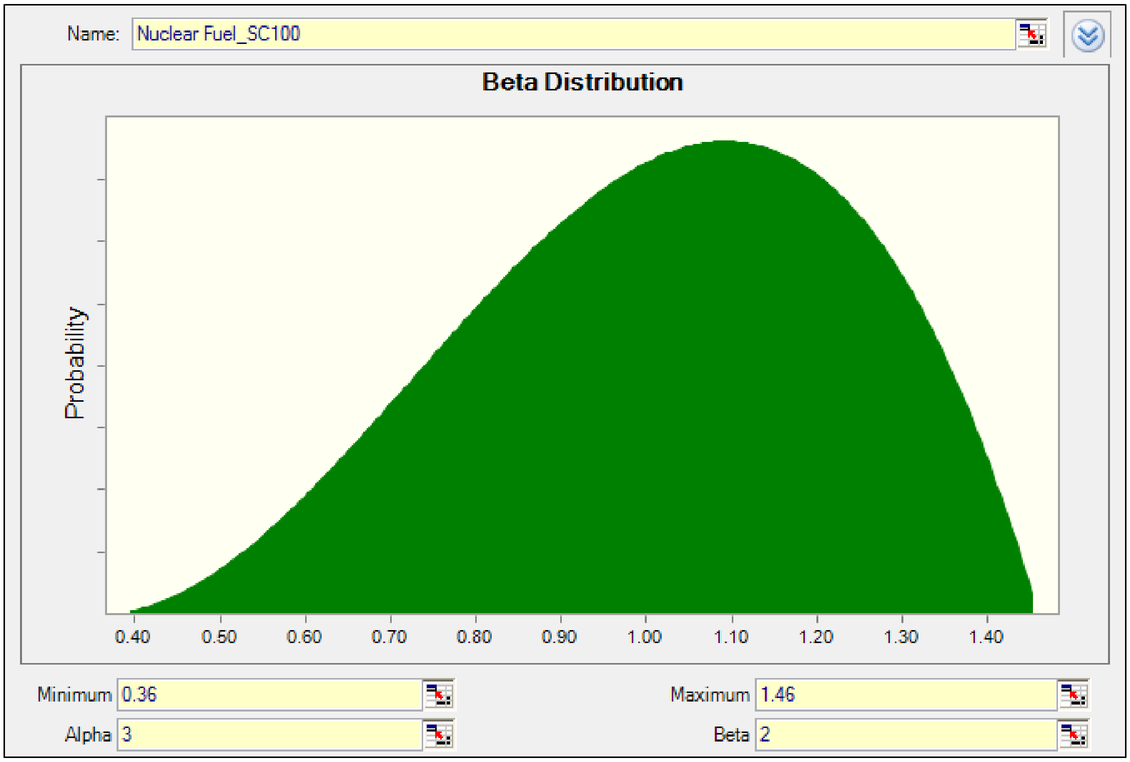
Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.51

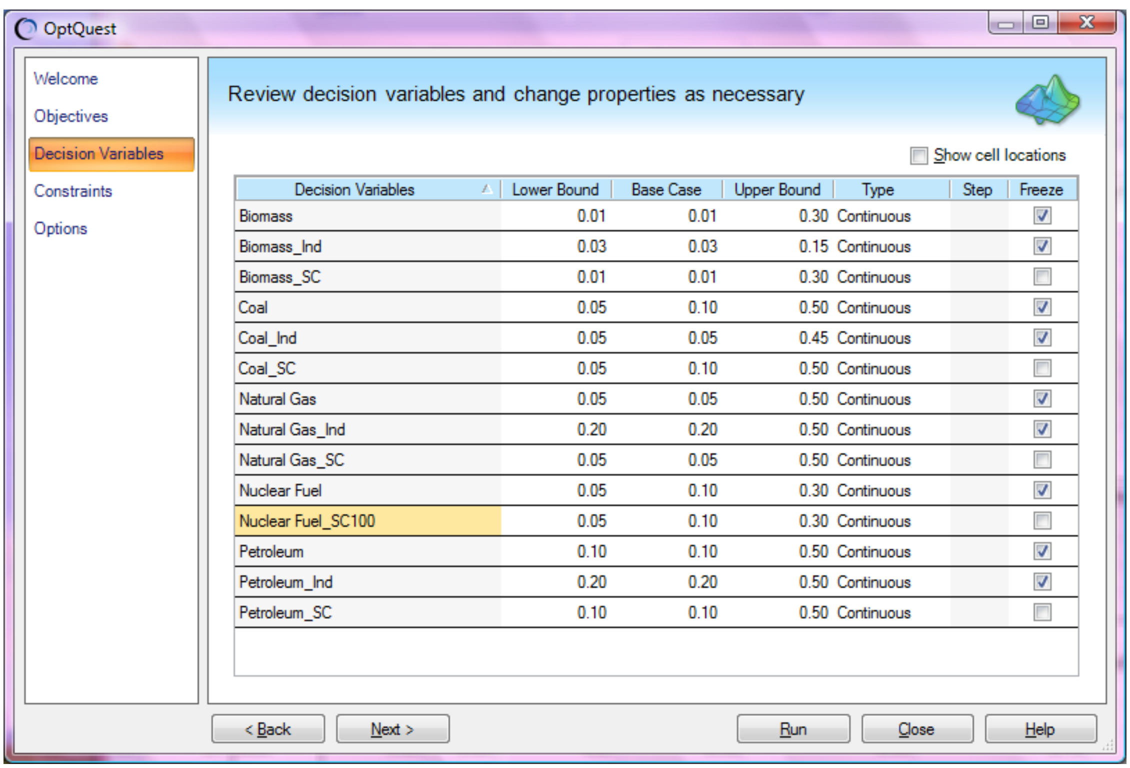
** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC + Natural Gas_SC + Nuclear Fuel_SC50 + Petr...	1.00	=	1.00

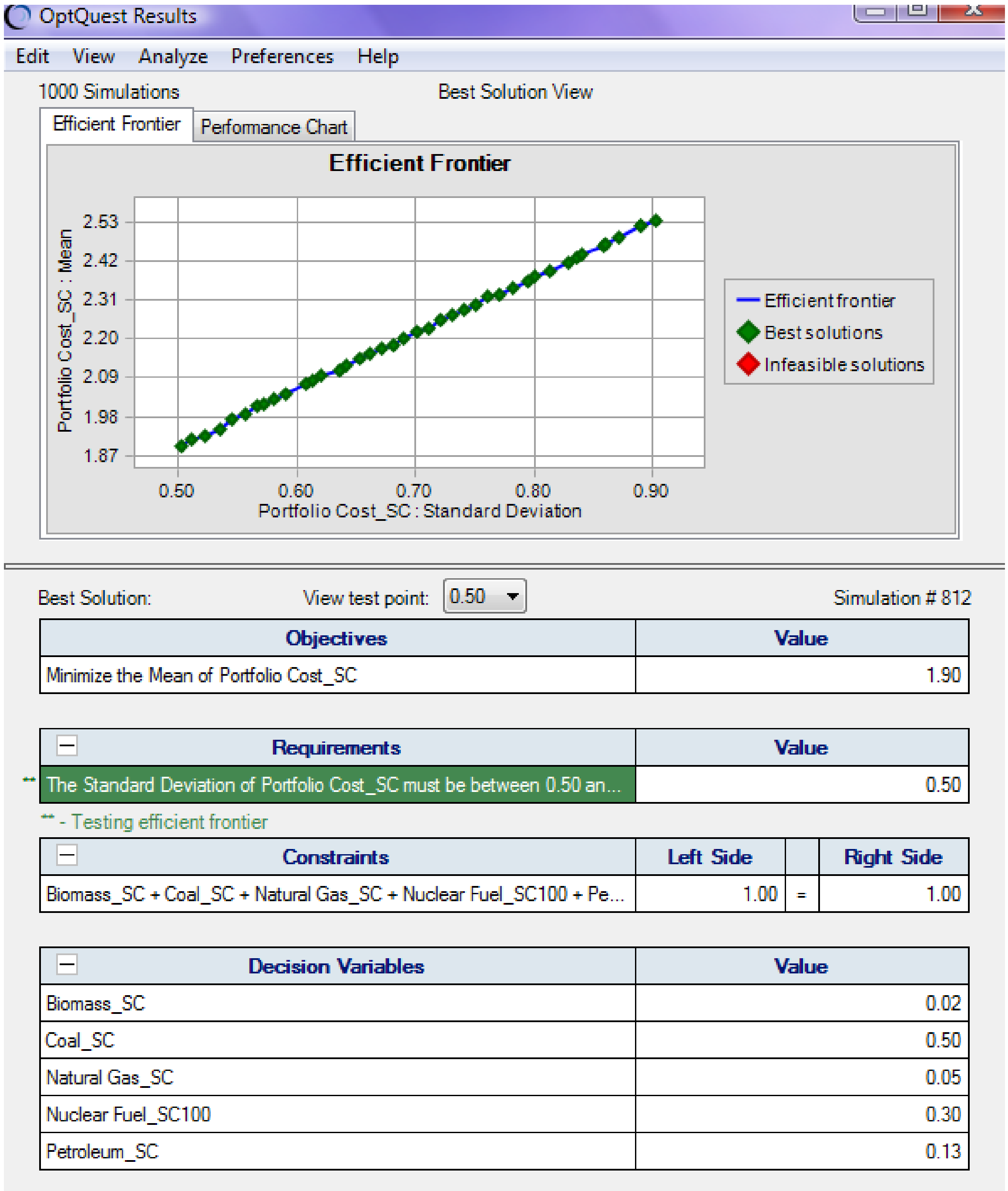
Decision Variables	Value
Biomass_SC	0.02
Coal_SC	0.50
Natural Gas_SC	0.05
Nuclear Fuel_SC50	0.30
Petroleum_SC	0.13

Scenario Three (Nuclear Fuel_ SC100): With 100% Social Cost

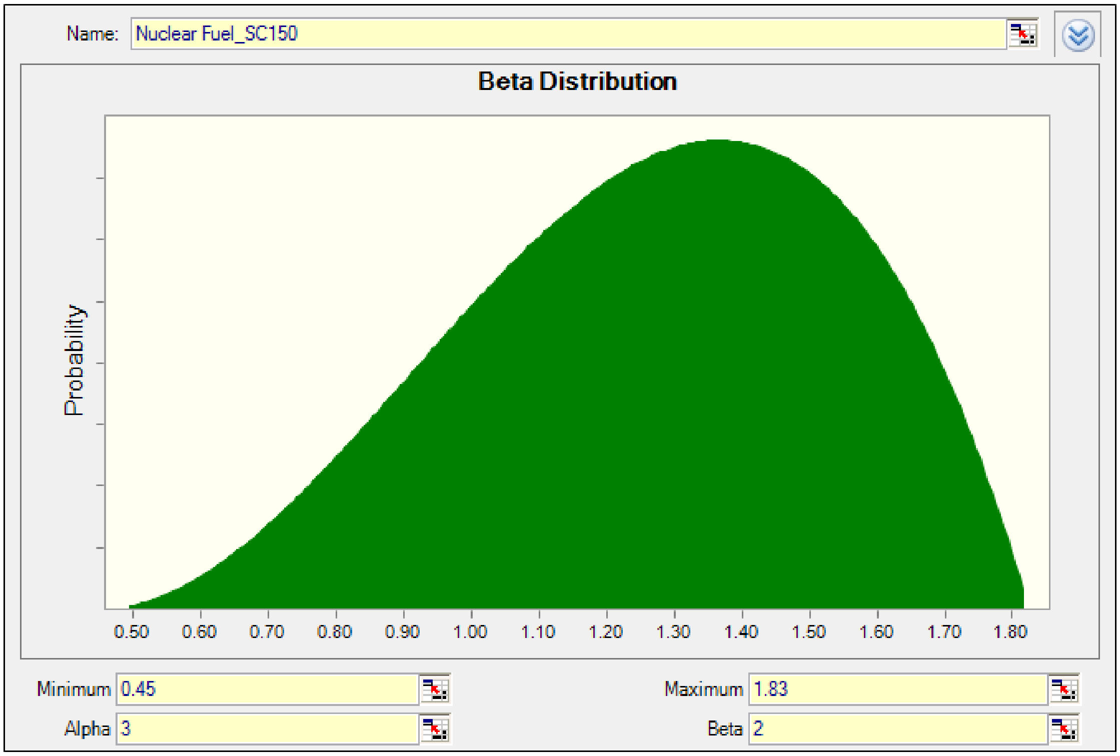


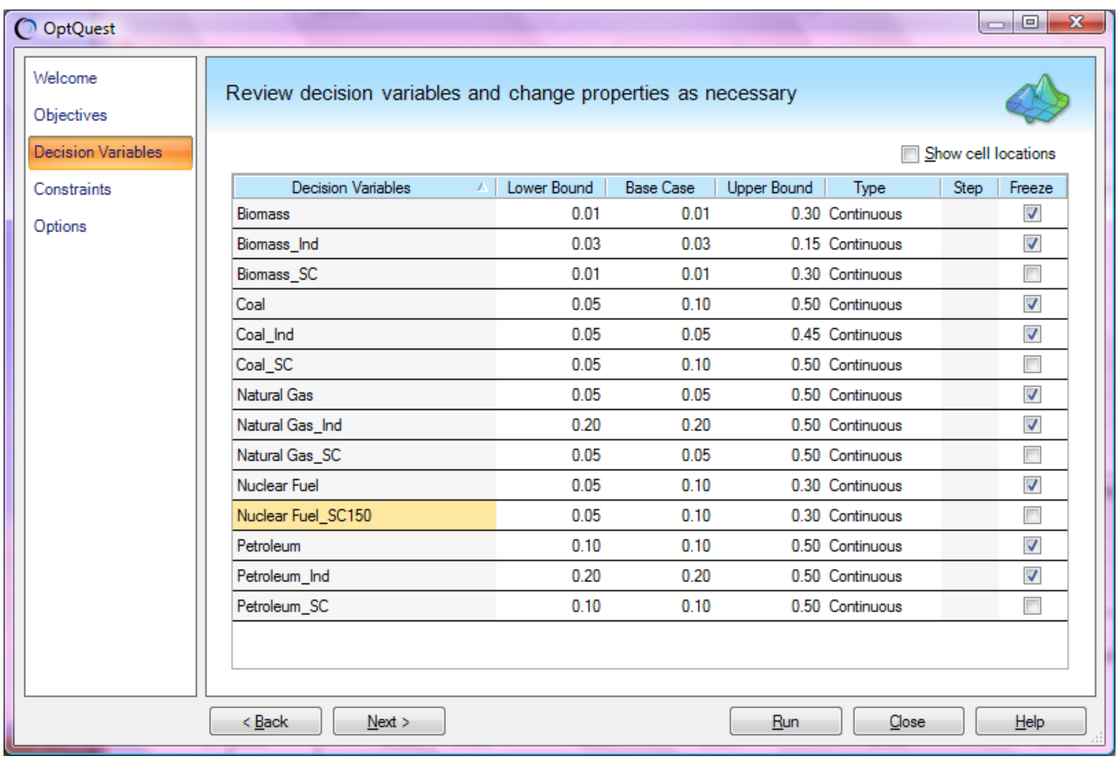


Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC100	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐


OptQuest Results
Edit View Analyze Preferences Help
1000 Simulations
Best Solution View
Efficient Frontier
Performance Chart
Efficient Frontier
Portfolio Cost_SC : Mean
2.53
2.42
2.31
2.20
2.09
1.98
1.87
0.50
0.60
0.70
0.80
0.90
Portfolio Cost_SC : Standard Deviation
Efficient frontier
Best solutions
Infeasible solutions
Best Solution:
View test point: 0.50
Simulation # 812
Objectives
Value
Minimize the Mean of Portfolio Cost_SC
1.90
Requirements
Value
The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...
0.50
** - Testing efficient frontier
Constraints
Left Side
Right Side
Biomass_SC + Coal_SC + Natural Gas_SC + Nuclear Fuel_SC100 + Pe...
1.00
=
1.00
Decision Variables
Value
Biomass_SC
0.02
Coal_SC
0.50
Natural Gas_SC
0.05
Nuclear Fuel_SC100
0.30
Petroleum_SC
0.13

Scenario Four (Nuclear Fuel_ SC150): With 150% Social Cost





Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC150	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐

OptQuest Results

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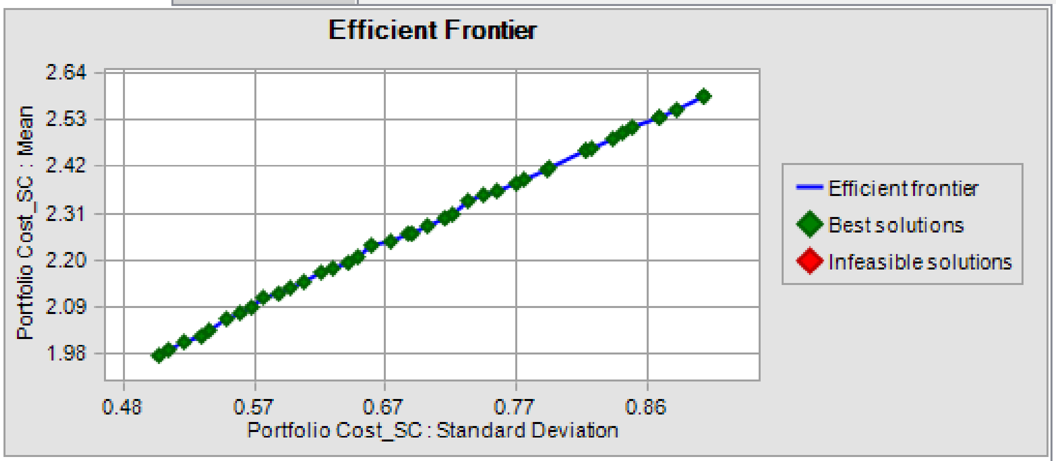


Best Solution: View test point: 0.50 Simulation # 31

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	1.98

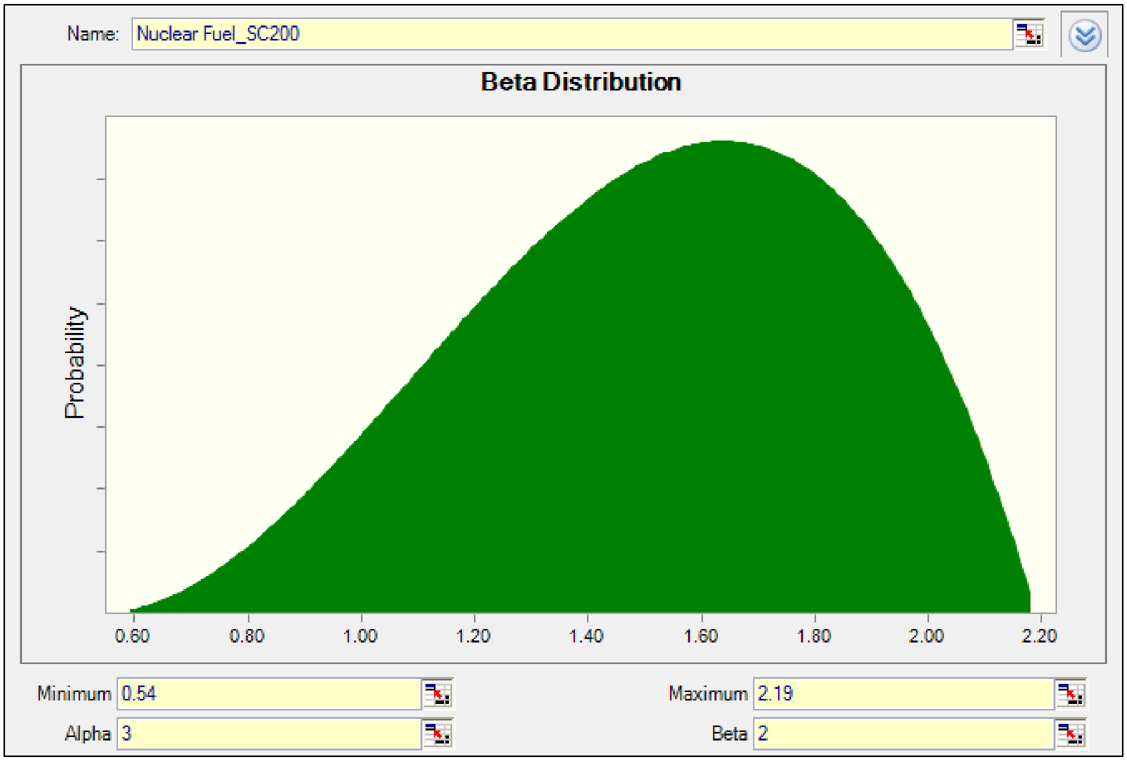
Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.50

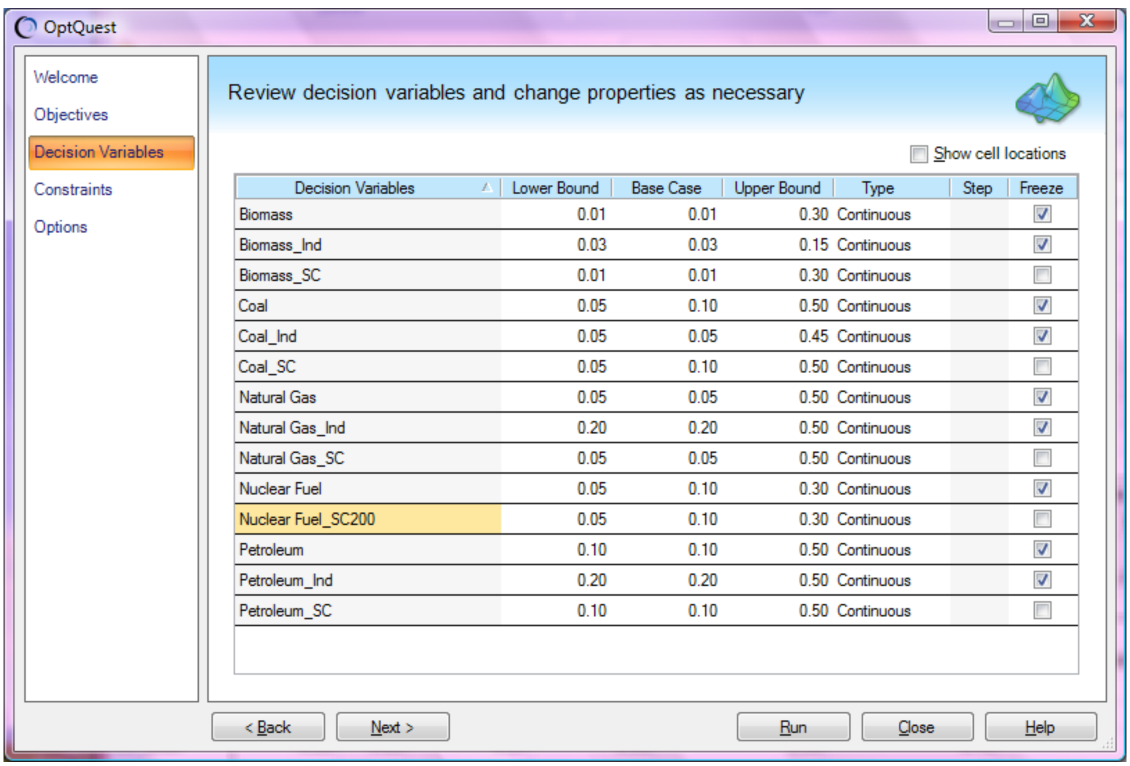
** - Testing efficient frontier

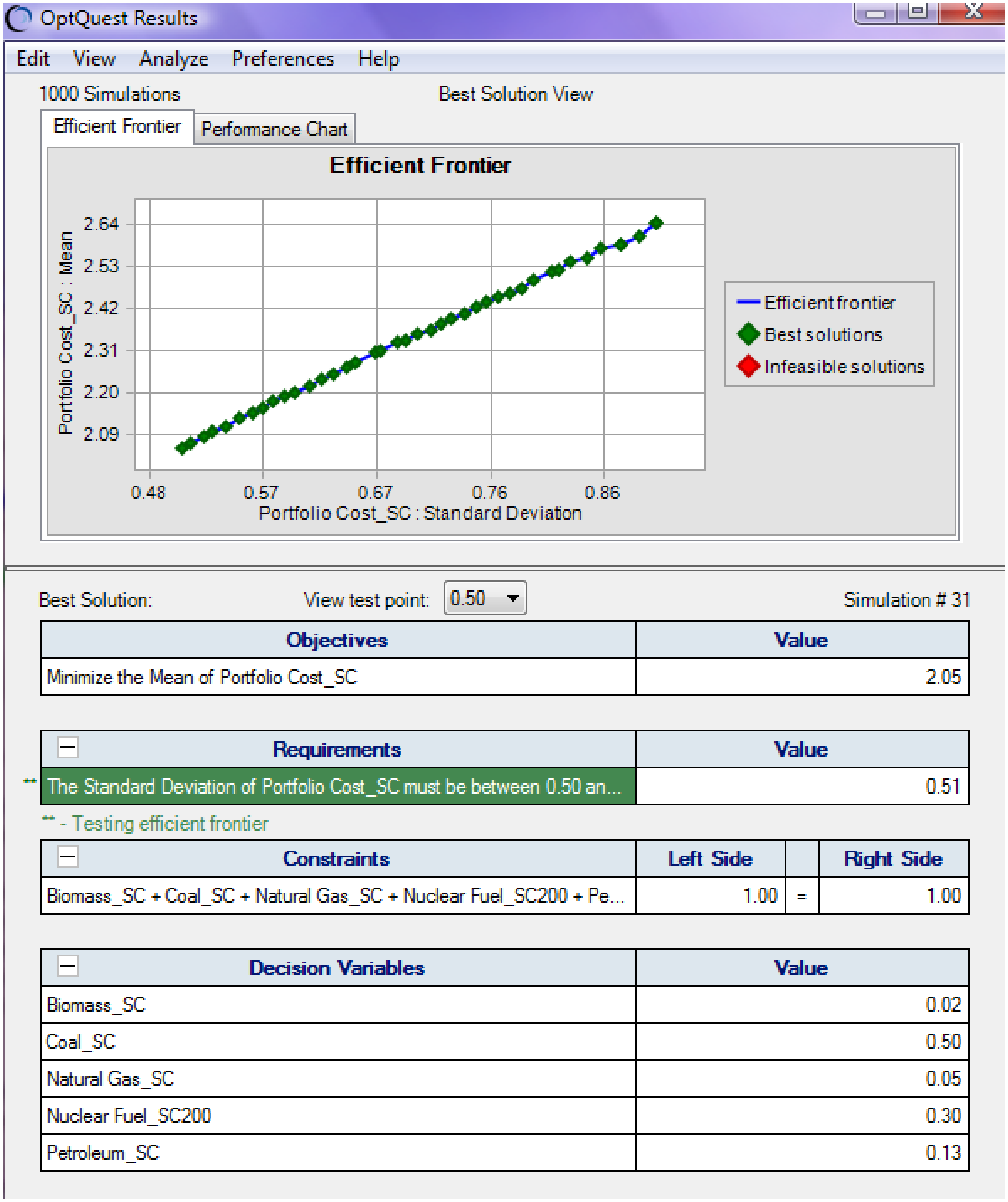
Constraints	Left Side		Right Side
Biomass_SC + Coal_SC + Natural Gas_SC + Nuclear Fuel_SC150 + Pe...	1.00	=	1.00

Decision Variables	Value
Biomass_SC	0.02
Coal_SC	0.50
Natural Gas_SC	0.05
Nuclear Fuel_SC150	0.30
Petroleum_SC	0.13

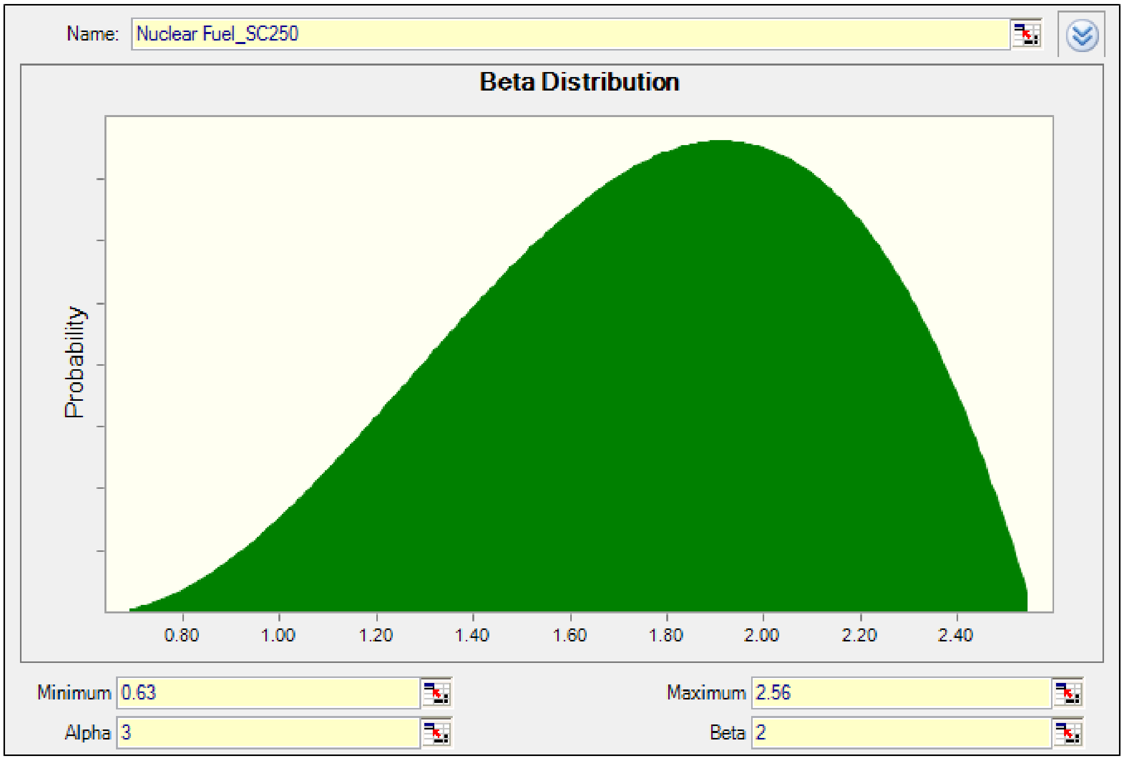
Scenario Five (Nuclear Fuel_ SC200): With 200% Social Cost

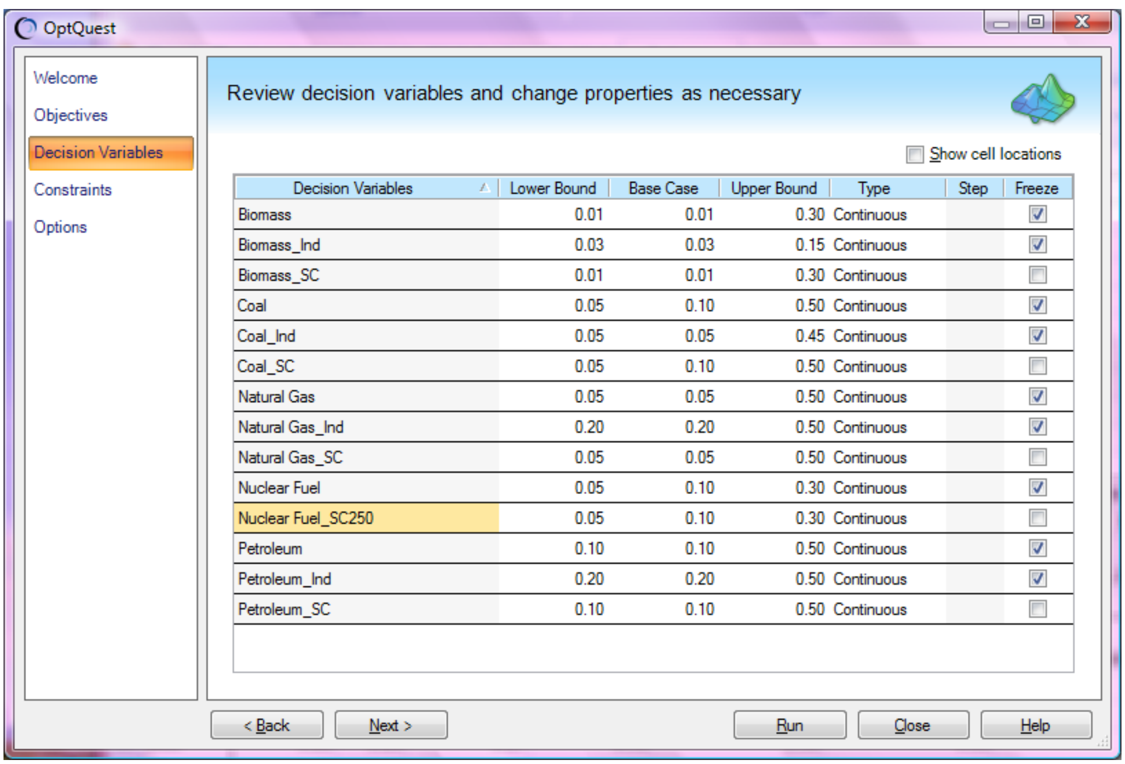





OptQuest Results
Edit View Analyze Preferences Help
1000 Simulations
Best Solution View
Efficient Frontier
Performance Chart
Efficient Frontier
2.64
2.53
2.42
2.31
2.20
2.09
Portfolio Cost_SC : Mean
0.48
0.57
0.67
0.76
0.86
Portfolio Cost_SC : Standard Deviation
Efficient frontier
Best solutions
Infeasible solutions
Best Solution:
View test point: 0.50
Simulation # 31
Objectives
Value
Minimize the Mean of Portfolio Cost_SC
2.05
Requirements
Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...
0.51
** - Testing efficient frontier
Constraints
Left Side
Right Side
Biomass_SC + Coal_SC + Natural Gas_SC + Nuclear Fuel_SC200 + Pe...
1.00
=
1.00
Decision Variables
Value
Biomass_SC
0.02
Coal_SC
0.50
Natural Gas_SC
0.05
Nuclear Fuel_SC200
0.30
Petroleum_SC
0.13

Scenario Six (Nuclear Fuel_ SC250): With 250% Social Cost





Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC250	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐

OptQuest Results

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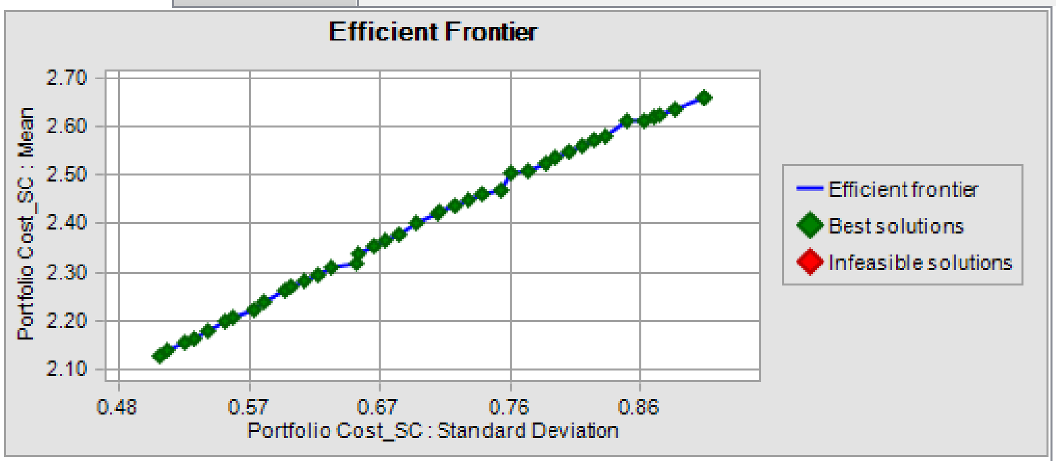
1000 Simulations Best Solution View

Efficient Frontier | Performance Chart



Best Solution: View test point: 0.50 Simulation # 31

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	2.13

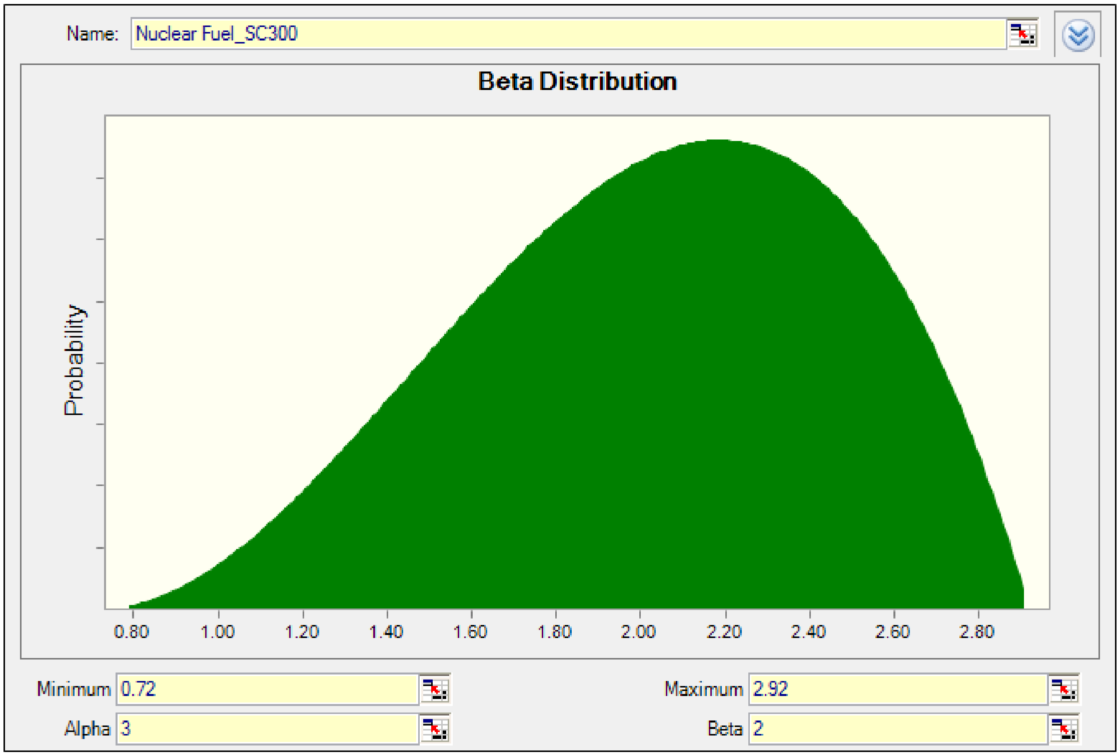
Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.51

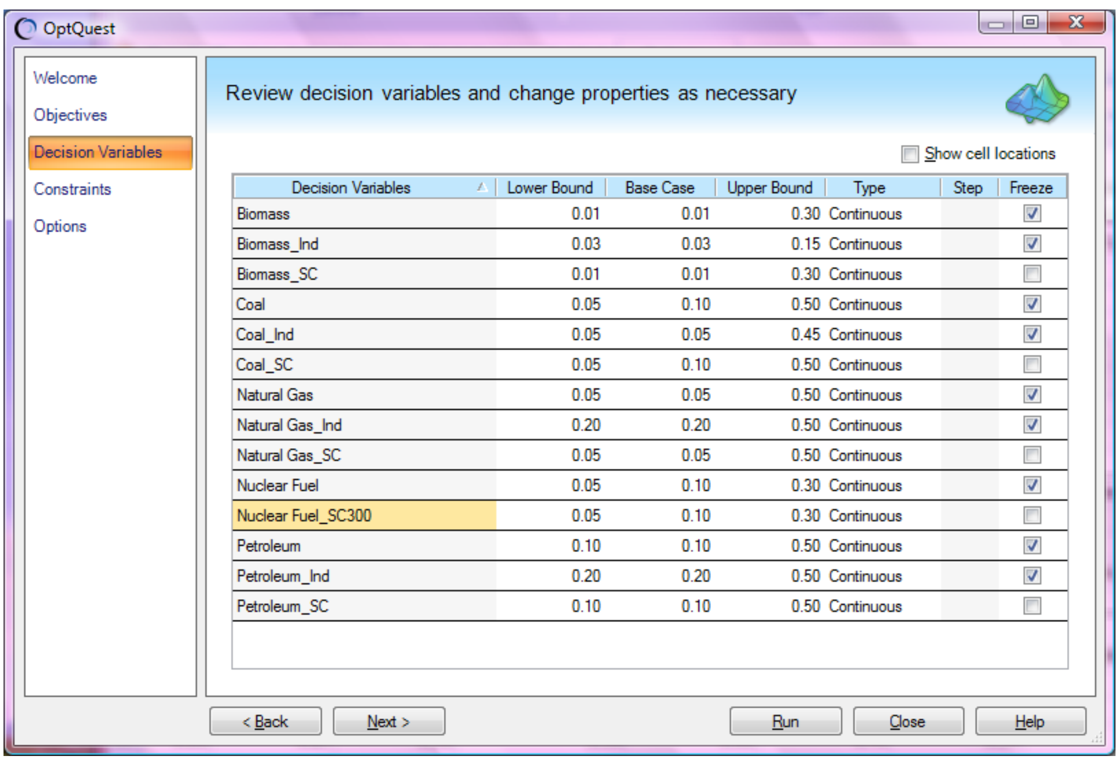
** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC + Natural Gas_SC + Nuclear Fuel_SC250 + Pe...	1.00	=	1.00

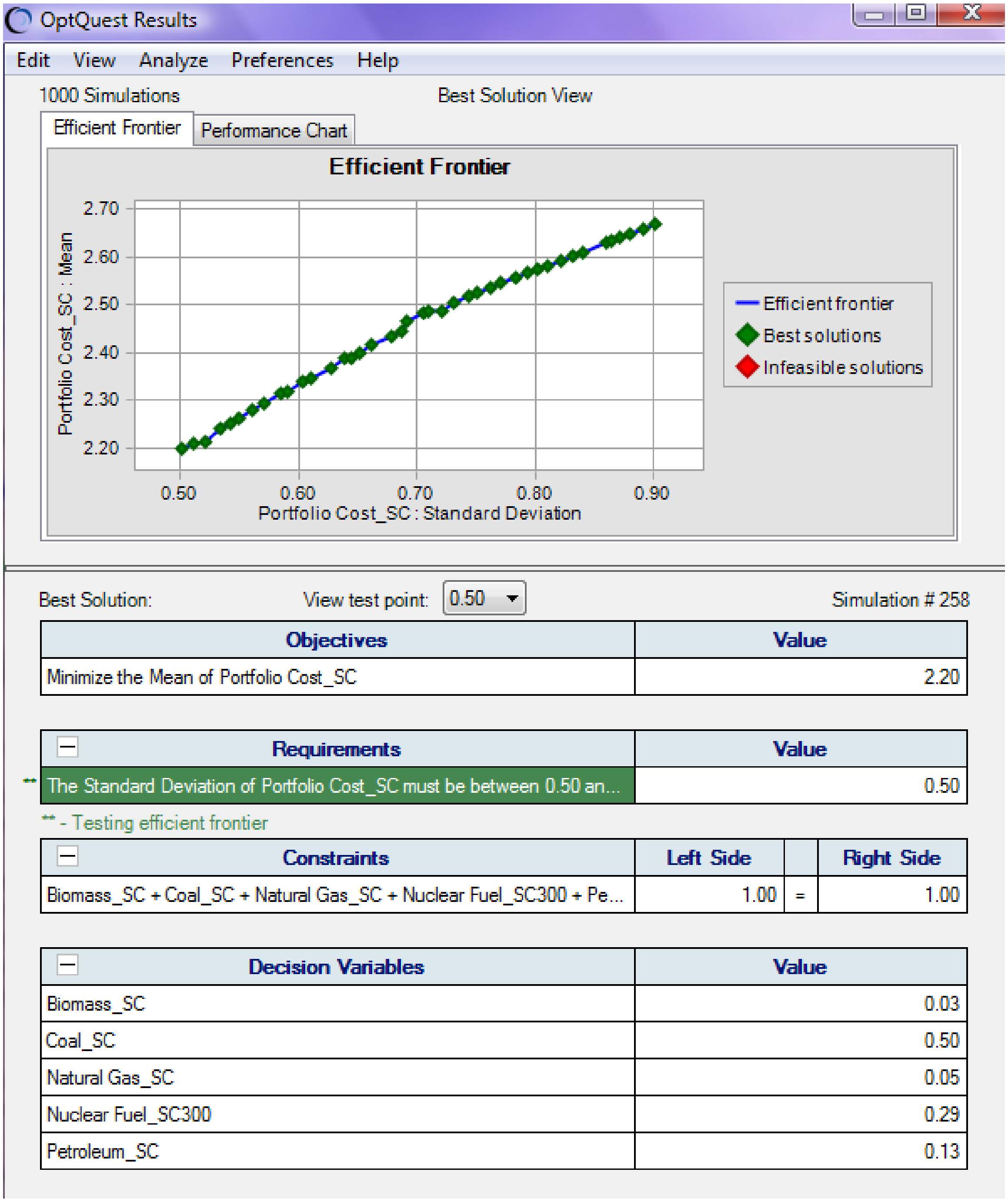
Decision Variables	Value
Biomass_SC	0.02
Coal_SC	0.50
Natural Gas_SC	0.05
Nuclear Fuel_SC250	0.30
Petroleum_SC	0.13

Scenario Seven (Nuclear Fuel_ SC300): With 300% Social Cost





Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC300	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐



Best Solution: View test point: 0.50 Simulation # 258

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	2.20

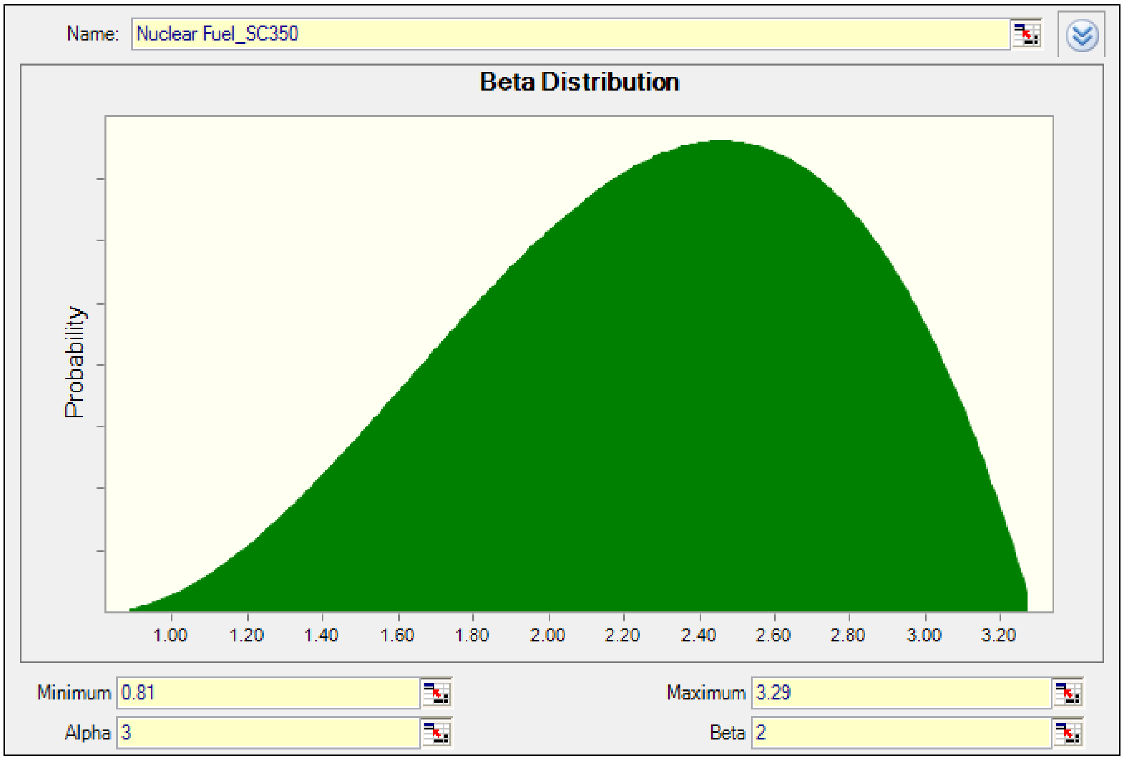
Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.50

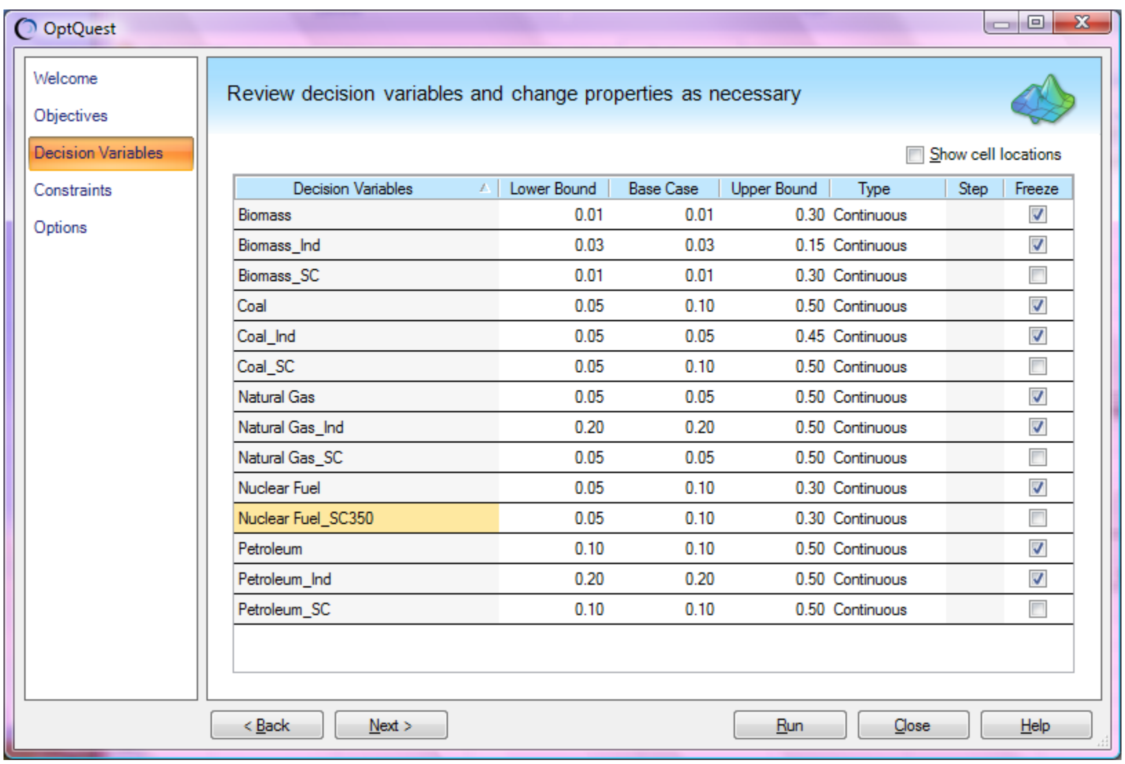
** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC + Natural Gas_SC + Nuclear Fuel_SC300 + Pe...	1.00	=	1.00

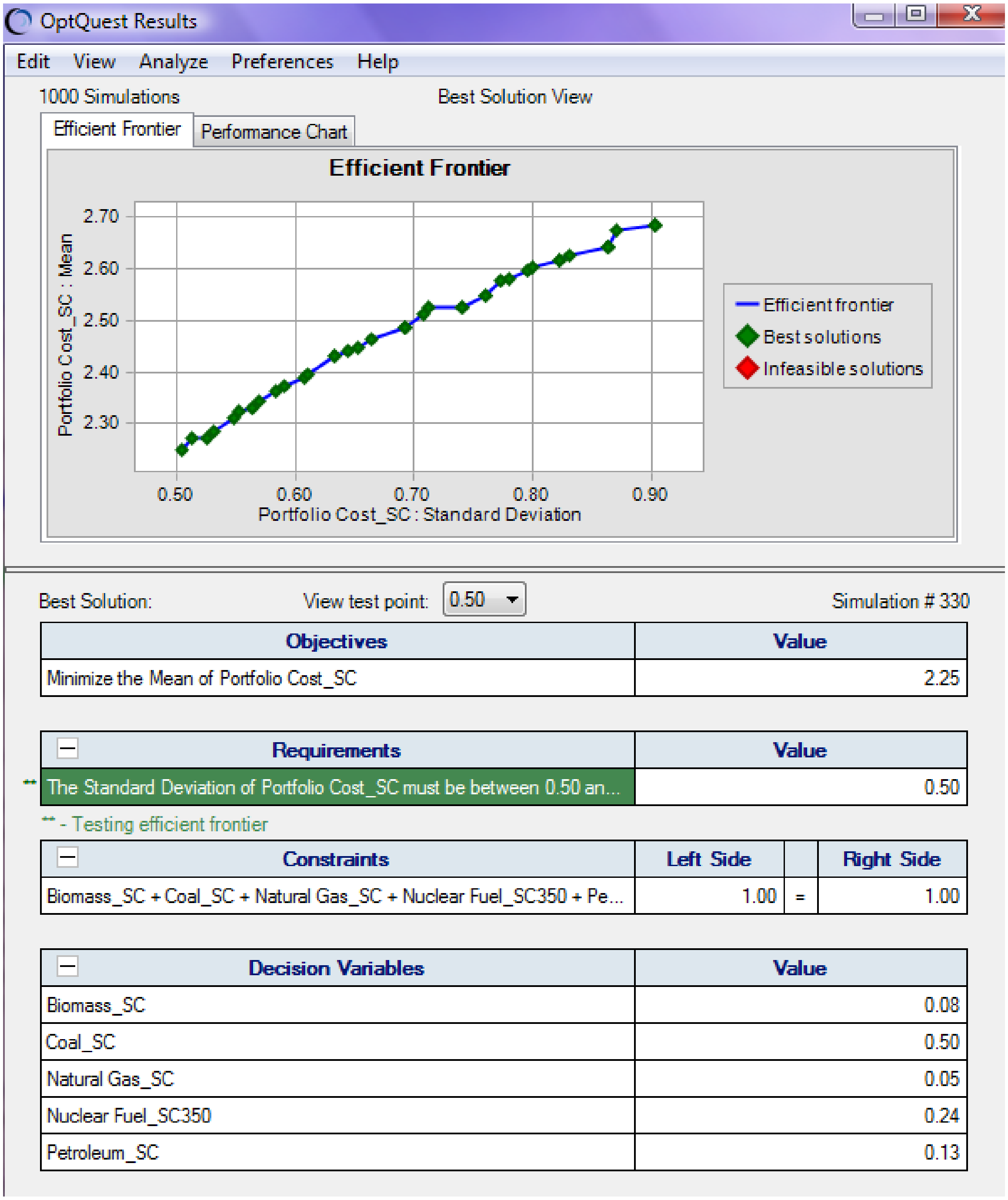
Decision Variables	Value
Biomass_SC	0.03
Coal_SC	0.50
Natural Gas_SC	0.05
Nuclear Fuel_SC300	0.29
Petroleum_SC	0.13

Scenario Eight (Nuclear Fuel_ SC350): With 350% Social Cost

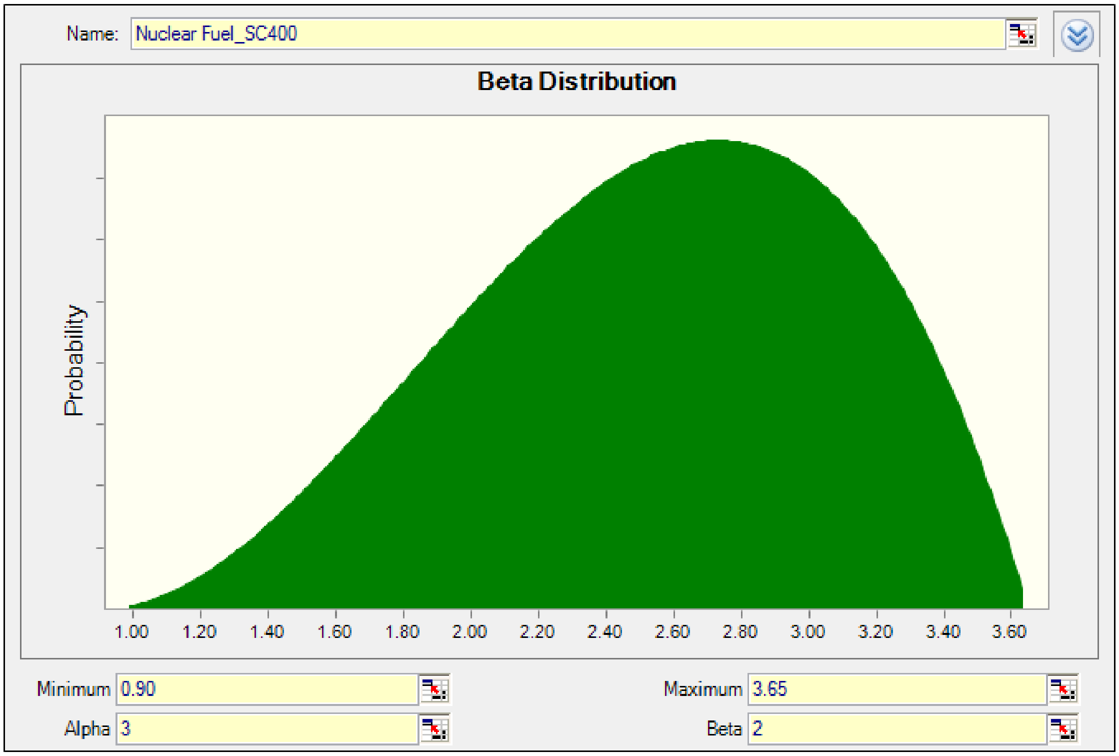


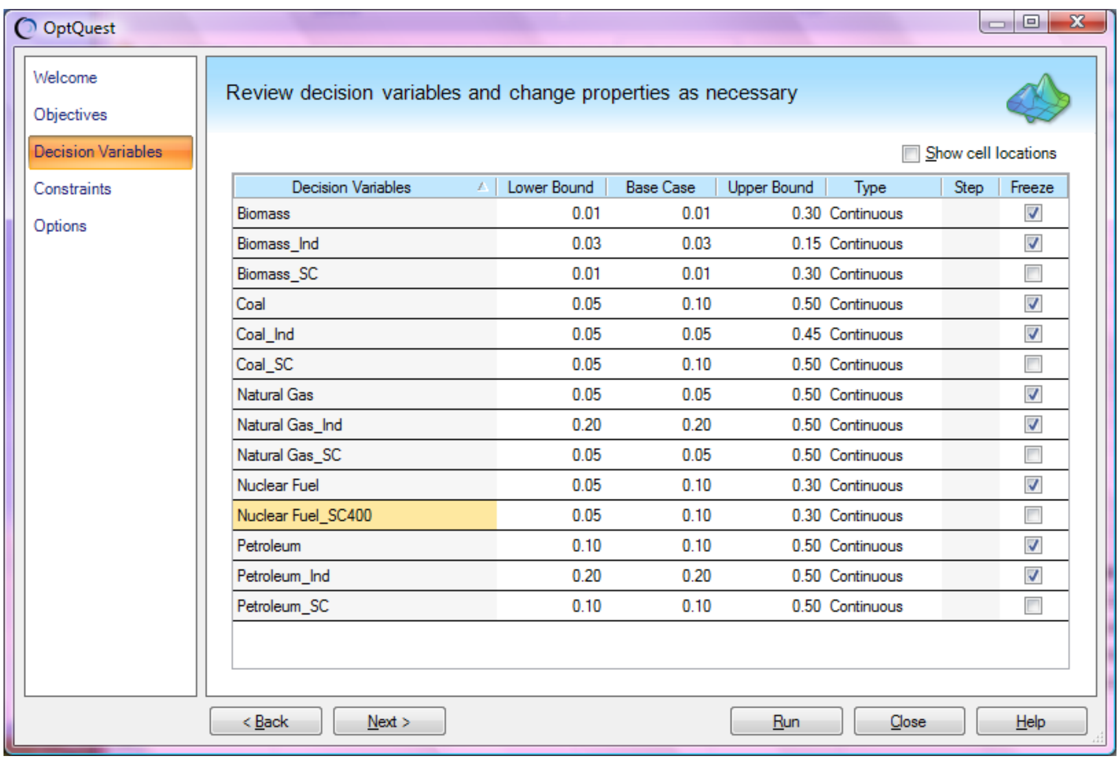


Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC350	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐


OptQuest Results
Edit View Analyze Preferences Help
1000 Simulations
Best Solution View
Efficient Frontier
Performance Chart
Efficient Frontier
Portfolio Cost_SC : Mean
2.70
2.60
2.50
2.40
2.30
0.50
0.60
0.70
0.80
0.90
Portfolio Cost_SC : Standard Deviation
Efficient frontier
Best solutions
Infeasible solutions
Best Solution:
View test point: 0.50
Simulation # 330
Objectives
Value
Minimize the Mean of Portfolio Cost_SC
2.25
Requirements
Value
The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...
0.50
** - Testing efficient frontier
Constraints
Left Side
Right Side
Biomass_SC + Coal_SC + Natural Gas_SC + Nuclear Fuel_SC350 + Pe...
1.00
=
1.00
Decision Variables
Value
Biomass_SC
0.08
Coal_SC
0.50
Natural Gas_SC
0.05
Nuclear Fuel_SC350
0.24
Petroleum_SC
0.13

Scenario Nine (Nuclear Fuel_ SC400): With 400% Social Cost





Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC400	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐

OptQuest Results

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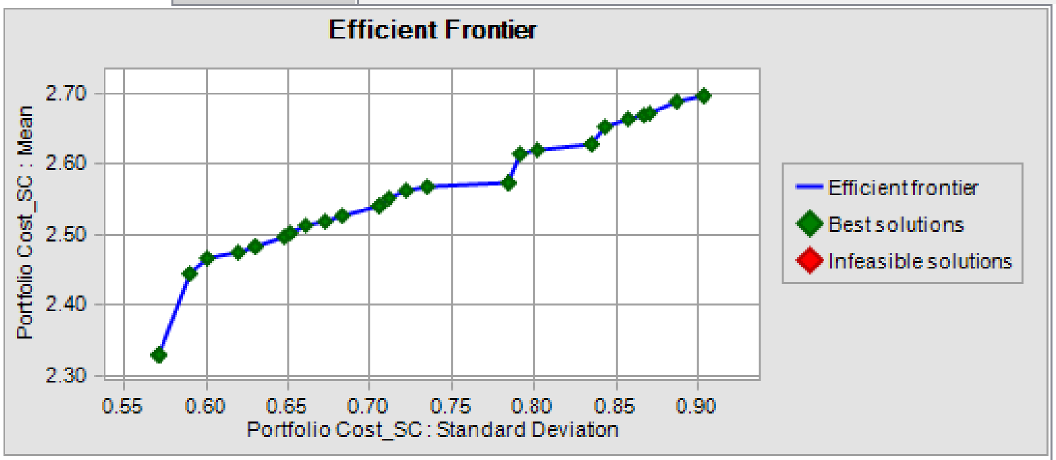
1000 Simulations Best Solution View

Efficient Frontier | Performance Chart



Best Solution: View test point: 0.50 Simulation # 906

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	2.33

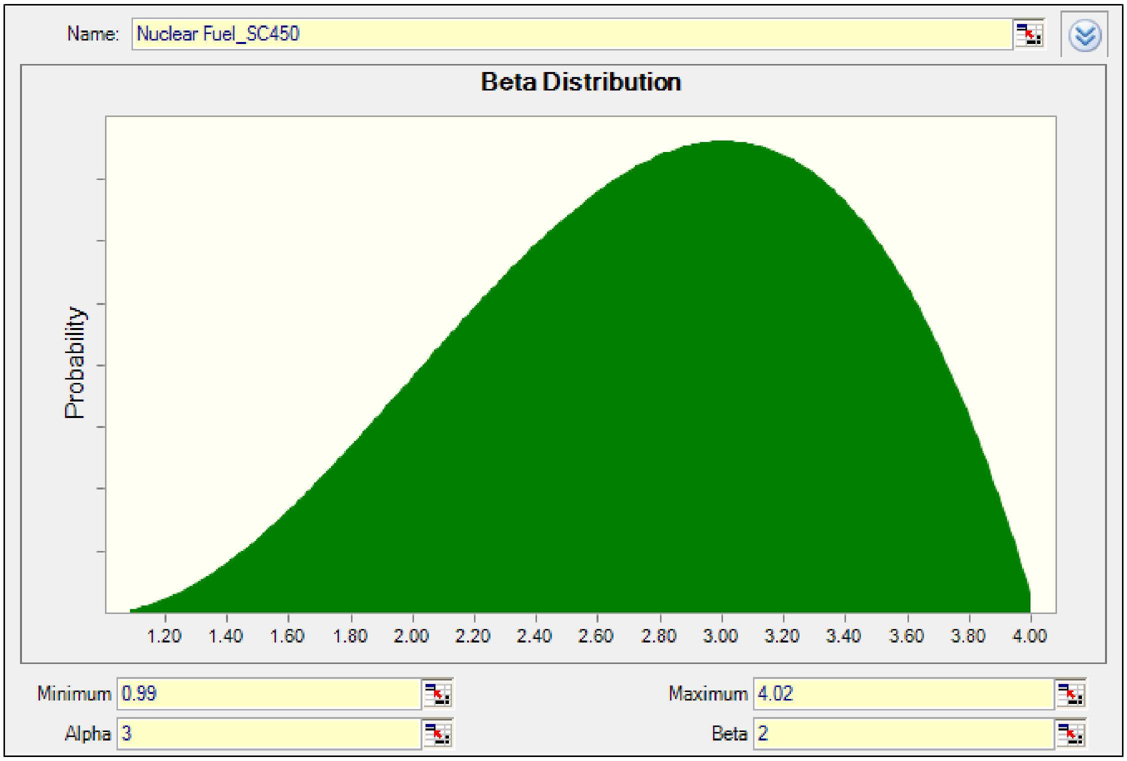
Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.57

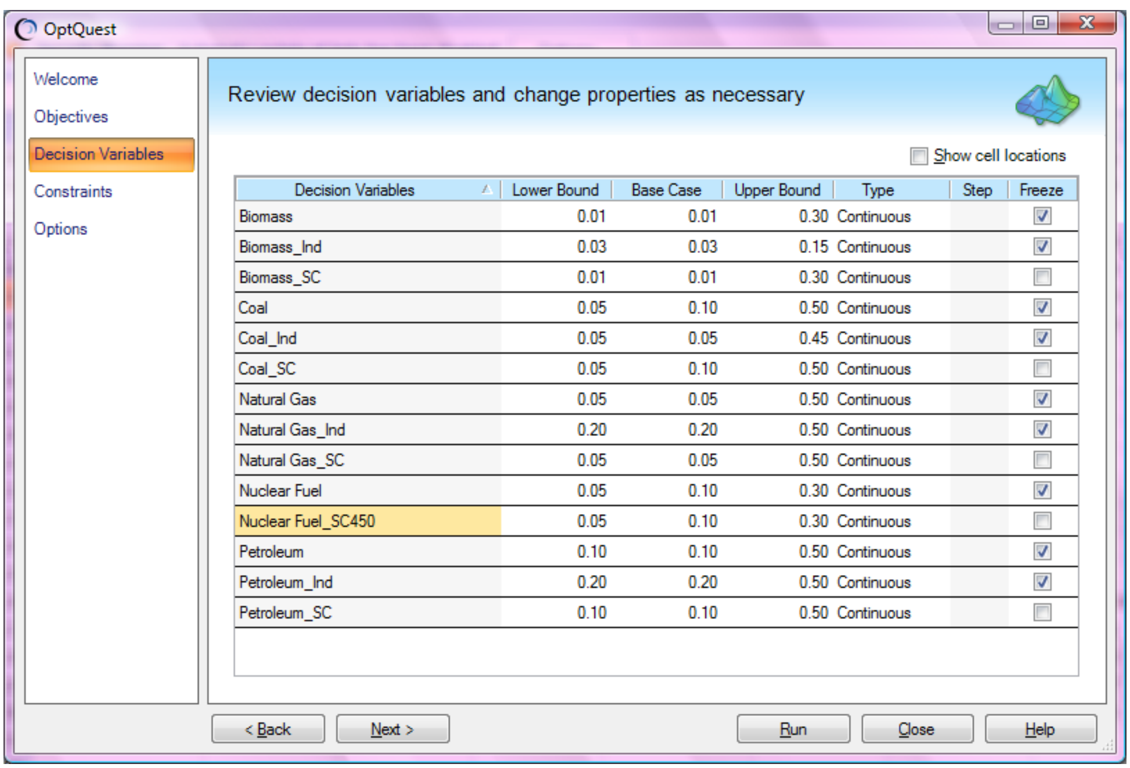
** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC + Natural Gas_SC + Nuclear Fuel_SC400 + Pe...	1.00	=	1.00

Decision Variables	Value
Biomass_SC	0.15
Coal_SC	0.50
Natural Gas_SC	0.05
Nuclear Fuel_SC400	0.15
Petroleum_SC	0.15

Scenario Ten (Nuclear Fuel_ SC450): With 450% Social Cost





Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC450	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐

OptQuest Results

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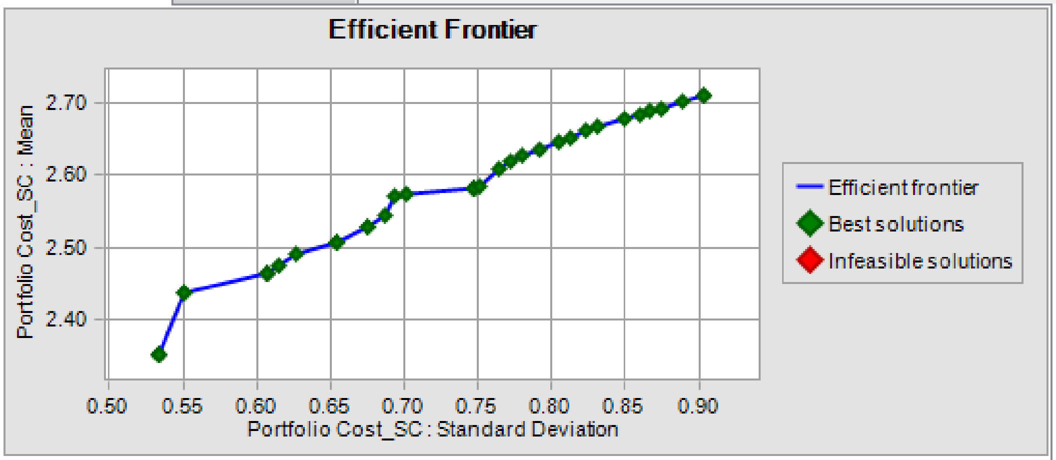
1000 Simulations Best Solution View

Efficient Frontier | Performance Chart



Best Solution: View test point: 0.50 Simulation # 441

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	2.35

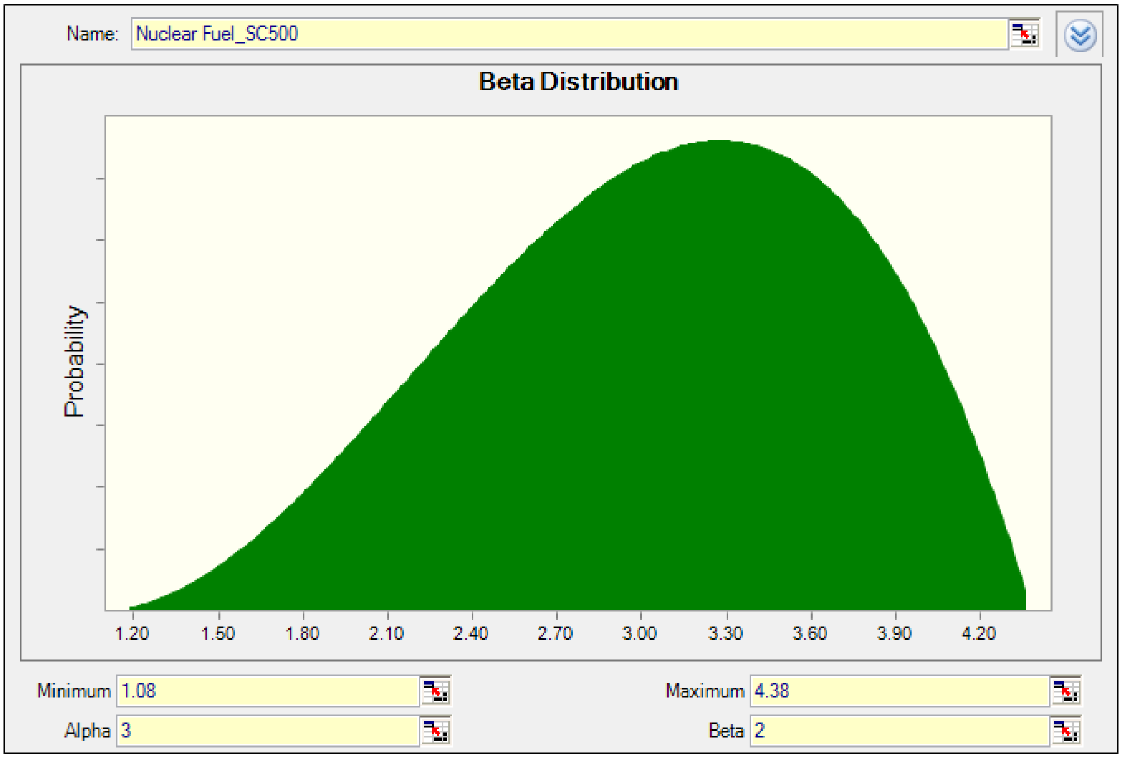
Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.53

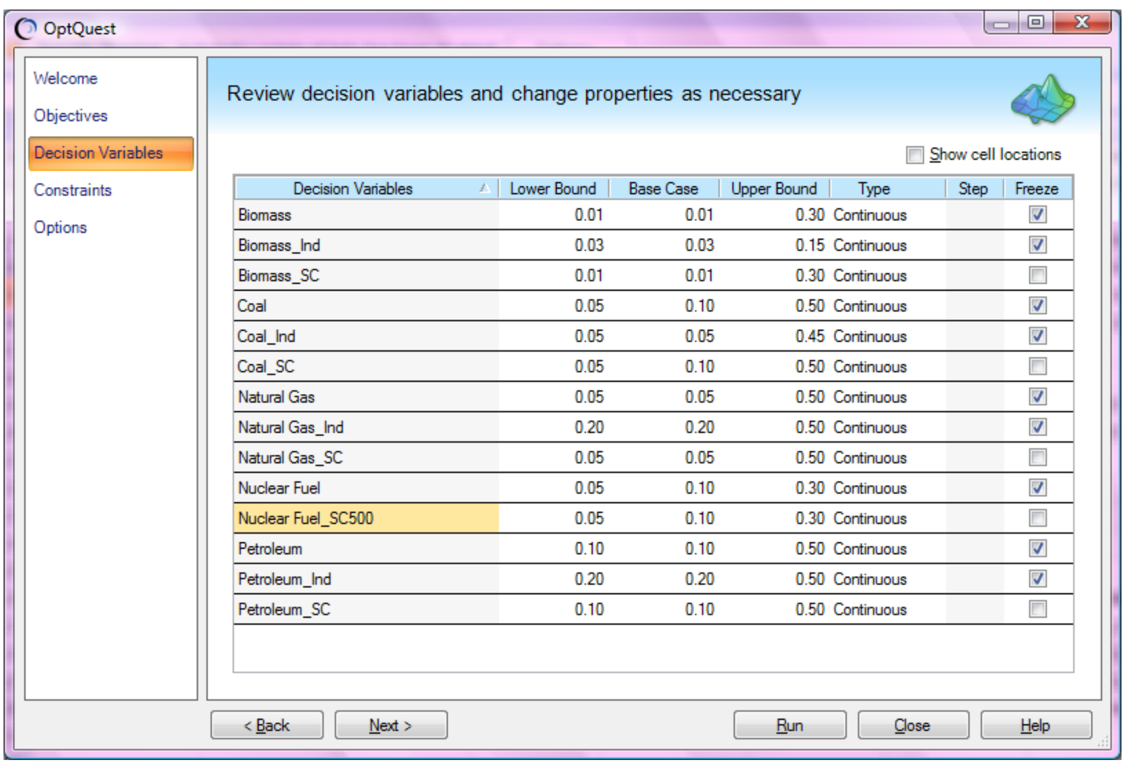
** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC + Natural Gas_SC + Nuclear Fuel_SC450 + Pe...	1.00	=	1.00

Decision Variables	Value
Biomass_SC	0.12
Coal_SC	0.50
Natural Gas_SC	0.15
Nuclear Fuel_SC450	0.13
Petroleum_SC	0.10

Scenario Eleven (Nuclear Fuel_ SC500): With 500% Social Cost





Decision Variables	Lower Bound	Base Case	Upper Bound	Type	Step	Freeze
Biomass	0.01	0.01	0.30	Continuous		☑
Biomass_Ind	0.03	0.03	0.15	Continuous		☑
Biomass_SC	0.01	0.01	0.30	Continuous		☐
Coal	0.05	0.10	0.50	Continuous		☑
Coal_Ind	0.05	0.05	0.45	Continuous		☑
Coal_SC	0.05	0.10	0.50	Continuous		☐
Natural Gas	0.05	0.05	0.50	Continuous		☑
Natural Gas_Ind	0.20	0.20	0.50	Continuous		☑
Natural Gas_SC	0.05	0.05	0.50	Continuous		☐
Nuclear Fuel	0.05	0.10	0.30	Continuous		☑
Nuclear Fuel_SC500	0.05	0.10	0.30	Continuous		☐
Petroleum	0.10	0.10	0.50	Continuous		☑
Petroleum_Ind	0.20	0.20	0.50	Continuous		☑
Petroleum_SC	0.10	0.10	0.50	Continuous		☐

OptQuest Results

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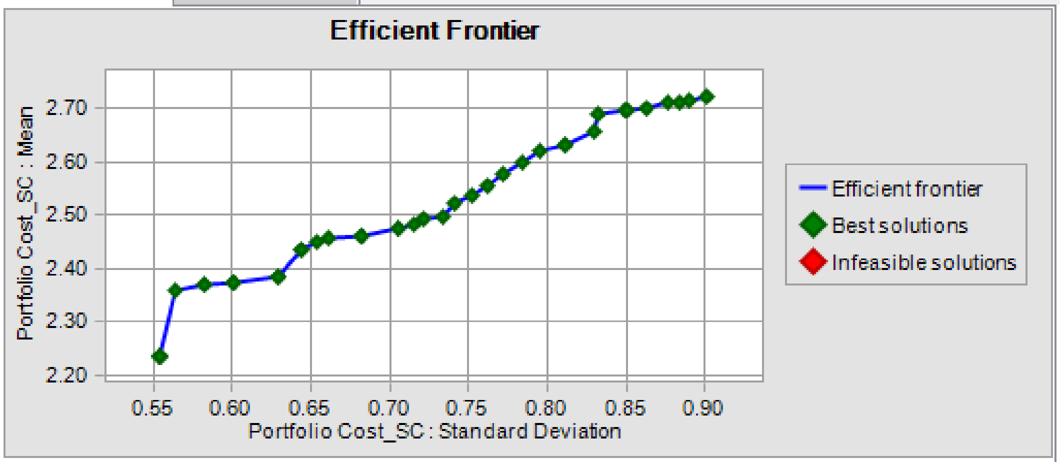
1000 Simulations Best Solution View

Efficient Frontier | Performance Chart



Best Solution: View test point: 0.50 Simulation # 905

Objectives	Value
Minimize the Mean of Portfolio Cost_SC	2.24

Requirements	Value
** The Standard Deviation of Portfolio Cost_SC must be between 0.50 an...	0.55

** - Testing efficient frontier

Constraints	Left Side		Right Side
Biomass_SC + Coal_SC + Natural Gas_SC + Nuclear Fuel_SC500 + Pe...	1.00	=	1.00

Decision Variables	Value
Biomass_SC	0.26
Coal_SC	0.50
Natural Gas_SC	0.05
Nuclear Fuel_SC500	0.05
Petroleum_SC	0.14