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A Study on Hubbert Peak of India's Coal: A System Dynamics Approach

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Abstract— American geophysicist M. King Hubbert in 1956 first introduced a logistic equation to estimate the peak and lifetime production for oil of USA. Since then, a fierce debate ensued on the so-called Hubbert Peak, including also its methodology. This paper proposes to use the VENSIM model to simulate Hubbert Peak, particularly for the India's coal production. At first the peak determined with intrinsic growth rate 0.062 and ultimate re-serve 285 billion tons. The Hubbert Peak for India's coal production appears to be in 2059 with a value of 3040.86 million tons. Later, sensitivity analysis has been made with different ultimate reserves and intrinsic growth rates.

Index Terms— Hubbert peak, coal, India, ultimate reserve, intrinsic rate, cumulative production, hubbert production

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1 Introduction

Access to modern energy services not only contributes to economic growth and household incomes but also to the improved quality of life that comes with better education and health services. All sources of energy will be needed to meet future energy demand, including coal. Coal has always been the bloodline of Indian economy. It plays a pivotal role out there. Coal is the most important and abundant fossil fuel in India. It accounts for 55% of the country's energy need. The country's industrial heritage was built upon indigenous coal. Commercial primary energy consumption in India has grown by about 700% in the last four decades. The current per capita commercial primary energy consumption in India is about 450 kgoe/year, which is well below that of developed countries. Driven by the rising population, expanding economy and a quest for improved quality of life, energy usage in India is expected to rise around 550 kgoe/year in 2015[1][2]. Considering the limited reserve potentiality of petroleum & natural gas, eco-conservation restriction on hydro project and geo-political perception of nuclear power, coal will continue to occupy center stage of India's energy scenario. With hard coal reserves around 246 billion tonnes, of which 92 billion tonnes are proven, Indian coal offers a unique ecofriendly fuel source to domestic energy market for the next century and beyond. Hard coal deposit spread over 27 major coalfields, are mainly confined to eastern and south central parts of the country. The lignite reserves stand at a level around 36 billion tonnes, of which 90 % occur in the southern State of Tamil Naidu[3]. As a result prediction over coal production peak value and time has become the most important issue for India. Hubbert peak could be used to estimate this.

In 1956, M. King Hubbert predicted that U.S. oil production would peak in the early 1970's and in 1971 Hubbert's prediction came true [4]. The production of oil appears to have gradual increase to a maximum output, then a long plateau and finally a slow decrease. This forms a curve which is called Hubbert Curve. This is done by placing a small number of small fields at the beginning a large number of small fields at the end. Hubbert argued that the following logistic equation can be used to estimate oil production:

$$P = aQ(1 - Q / R) \qquad (1)$$

Where P identifies the annual production of oil, 'Q' identifies the cumulative production which can be calculated from P, and R is the cumulative production after all recoverable oil has been produced. "a" is a parameter which is called intrinsic growth rate.

This equation can be also written as,

$$P / Q = a - aQ / R \qquad (2)$$

Or

$$P / Q = a - mQ \qquad (3)$$

In equation (3), the parameter "m" shows the production of oil (a / R). Figures below show the estimation of US production. Only problem here is the values of 'a' and 'm' are ambiguous found using statistical regression for accuracy. So there is no exact value. But so far this technique is the best way to estimate the peak value of natural resources.

Fig. 1. Hubbert Curve.

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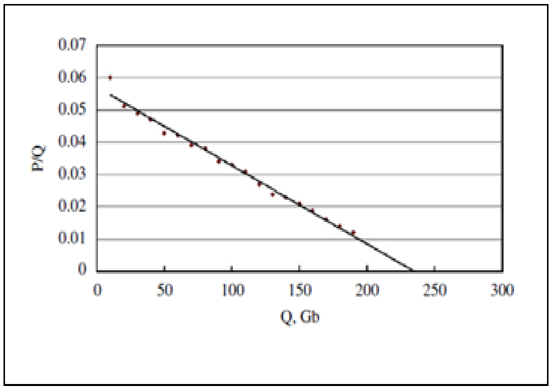

Fig.2. Estimation of US production.

In this paper a system dynamics approach is used to examine the Hubbert peak of India's coal production. In section 2, the related literature of system dynamics with the reason why it is used in order to study the India's coal production outlook, is explained. In section 3 a system dynamics model of India's coal Hubbert peak is proposed. The model is simulated for 190 years and the results are illustrated. The value of this simple model is to help researchers in scenario building and sensitivity analysis. Here two types of sensitivity analysis have been generated. At first, the variation in Hubbert peak due to Ultimate reserve is figured out and then for different intrinsic growth rate. Thus, it offers more informative results for better energy policy decisions.

2 SYSTEM DYNAMICS

System dynamics is a field of study that Jay Forrester founded at the Massachusetts Institute of Technology (MIT) in the 1950s. The field has a long history, and has drawn from other fields as diverse as mechanical engineering, biology, and the social sciences. In its simplest sense, system dynamics focuses on the flow of feedback (information that is transmitted and returned) that occurs throughout the parts of a system—and the system behaviors that result from those flows. For example, system dynamists study reinforcing processes—feedback flows that generate exponential growth or collapse—and balancing processes—feedback flows that help a system maintain stability. SD prides itself on combining human mind and the power of computers in order to overcome the barriers to learning such as dynamic complexity, limited information of problem situation, confounding variables and ambiguity, bounded rationality, flawed cognitive maps, erroneous inferences about dynamics, and judgmental errors [5].

In this paper, SD methodology is accepted for to achieve a realistic and reflective system from a greater understanding of the target system. It has some flexibility which can be described as:

The purpose is to clearly identify the problem and the factors oriented with the system.

The relationship of all the factors with the target system is very easy to define. A sign causal diagram is drawn in order to develop the understanding of influence of the variables on each other. Explicit concepts of SD such as flows, levels and auxiliary are used in simulation model building process.

After the implementation and simulation of the model, it is possible to further analysis the sensitivity for different scenarios that helps the policy makers more robust decision.

However, this model is based on the historical data and cannot be 100% accurate as future may not follow the past. But clearly it gives an indication of the future production.

2.1 CAUSALITY & FEEDBACK

Causal loop diagrams (CLDs) are an important tool for representing the feedback structure of systems. A causal diagram consists of variables connected by arrows denoting the causal influences among the variables. The important feedback loops are also identified in the diagram. There is an Example of a Causal Loop.

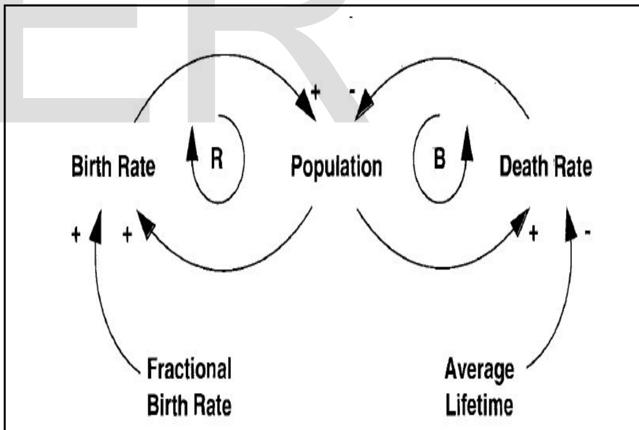

Fig. 3. Causal Loop Diagram.

Variables are related by causal links, shown by arrows. In the example, the birth rate is determined by both the population and the fractional birth rate. Each causal link is as-signed a polarity, either positive (+) or negative (-) to indicate how the dependent variable changes when the independent variable changes. The important loops are highlighted by a loop identifier which shows whether the loop is a positive (Reinforcing) or negative (Balancing) feedback. The loop identifier circulates in the same direction as the loop to which it corresponds. In the example, the positive feedback relating births and population is clockwise and so is its loop identifier; the negative death rate loop is counter-clockwise along with its identifier. A '+' link means that if the cause increases, the effect in-creases above what it would otherwise have been, and if the cause decreases, the effect de-creases below what it would otherwise have been. In the example an increase in the fractional birth rate means the birth rate (in people per year) will increase above what it would have been, and a decrease in the fractional birth rate means the birth rate will fall below what it would have been. That is, if average fertility rises, the birth rate, given the population, will rise; if fertility falls, the number of births will fall. A '-' link means that if the cause increases, the effect de-creases below what it would otherwise have been, and if the cause decreases, the effect increases above what it would otherwise have been. In the example, an increase in the aver-age lifetime of the population means the death rate (in people per year) will fall below what it would have been, and a decrease in the average lifetime means the death rate will rise above what it would have been. That is, if life expectancy increases, the number of deaths will fall; and if life expectancy falls, the death rate will rise.

2.2 LEVEL AND RATE

Although CLD causes in improved communication and comprehensiveness among users, only a map of causal influences and feedback loops is not enough to determine the dynamic behavior of a system. There are two variables required for simulating all elements inside a system, level and rate. The 'level' refers to a given element within a specific time interval, e.g. inventory level on December 2011 or current total students in a university and so on. Meanwhile, the rate reflects the extent of behavior of a system, such as hourly production volume, and daily sales turnover. In simple words 'level' means- an accumulation or integration of information & 'rate' means- an increasing or decreasing amount of flow. A time factor is the main concern. Specifically, the differences between the level and the rate de-pend on whether the element contains a time factor or not [6]. The level is calculated from the difference between a rate variable that increases the level and a rate variable that reduces the level. A value of level (an accumulated rate) can be identified easily, but a rate is not easy to be identified. The level and the rate can be formulated using the stock-flow diagram (SFD) for a simulation test.

3 SYSTEM DYNAMICS MODEL OF HUBBERT PEAK FOR INDIA'S COAL

A simple SD model is implemented based on Mr. Hubbert's equation. Figure 4 shows the casual loop diagram of Hubbert's equation. The explanation of this loop is that an increase in Hubbert Production causes a rise in cumulative production. This increase with regard to the amount of ultimate reserves, cause an increase in "cumulative production/ultimate reserves" ratio. As this ratio rises in the presence of the intrinsic growth rate, the production decreases due to resource depletion.

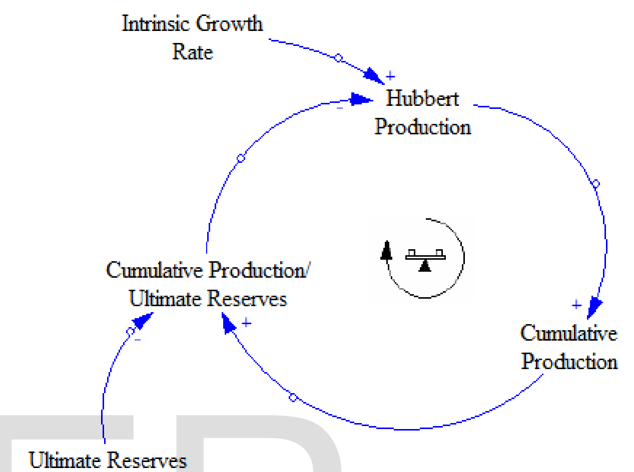

Fig. 4. Causal Causal loop Diagram of Hubbert Peak.

A time horizon of 190 years is defined to show the history of India's coal production and its changes in the future. Two levels have been developed in this model, (1) Ultimate Reserve and (2) Cumulative Production. The Ultimate Re-serve does not have any inflows. This is because coal is created in geologic time. Thus, for all practical purposes, the total amount of coal is assumed to be constant. The Ultimate Reserves are conducted into the Cumulative Production with the rate of Hubbert production which is affected by the intrinsic growth rate. Based on India's coal data, the intrinsic growth rate is 0.062. The historical data for Export, Import and total coal (Black Coal & Brown Coal) are added with lookup variable which are named Export lookup, Import lookup and Total coal lookup respectively. The data is obtained from Geological Survey of India [7]. The model's equations are given in the Appendix.

The model shows that Indian coal production will reach its peak in 2059 with 3040.86 million tones/year as shown in figure 6. This model is free from all type of policies. In the Indian energy projections to 2029-30 the primary energy consumption by fuel the use of coal is reduced by annually 0.8% and 0.7% for black coal and brown coal respectively [8].

There will be a right shift in the Hubbert peak curve if this policy is considered. The total economic recoverable black and brown coal reserve for India is 285 billion tons [9]. Here this paper considers recoverable black coal and brown coal resources in India as 84 billion tons. The value of export growth rate is used as 2.4% per year taken from the ABARES. One more assumption is considered regarding the total coal. At presently, because of the CO2 emissions the use of coal is discouraged in India. Hence, no growth rate is used for the total coal amount which means no further increase of domestic consumption.

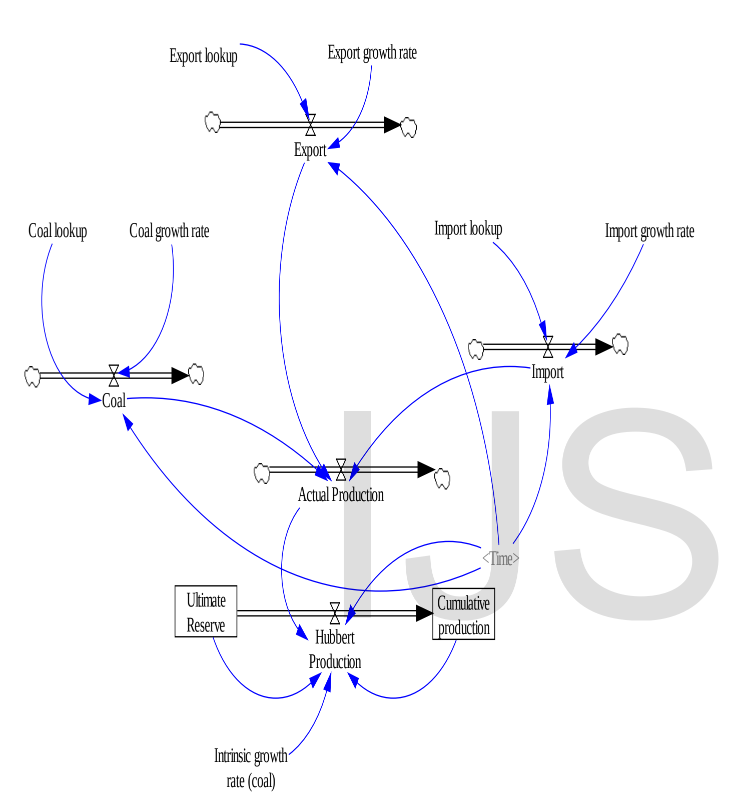

Fig.5. Stock-flow Diagram of Hubbert Peak of Indian Coal.

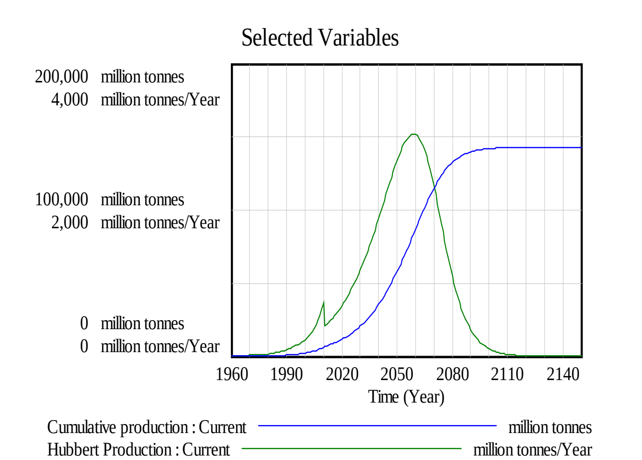

Fig.6. The Stock-flow Diagram of Hubbert Peak.

TABLE 1
SIMULATION RESULTS OF HUBBERT PRODUCTION RATE AND CUMULATIVE PRODUCTION

Time (Year)	Cumulative production(million tons/year)	Hubbert Production(million tons)
2057	77831.9	3020.16
2058	80852	3035.87
2059	83887.9	3040.86
2060	86928.8	3034.49

3.1 SENSITIVITY ANALYSIS

The behavior of the model is important and informative under some scenarios as implemented in this paper. Ultimate Reserve and the Intrinsic Rate are the very difficult to figure out for a range of time. There is a big disparity in these values from source to source. Hence, in the analysis of coal production, first scenario is about Ultimate Reserves (UR). Three different amounts are used for UR 275862,285862 and 295862 million tons. Figure 7 and Table 2 show the behavior of India's coal production under these conditions. The results show that when the ultimate reserves vary from lower to higher amount, with the same intrinsic growth rate, the production peak will occur in longer time with higher production amount. In the Figure 7 the green, red and blue lines are indicating UR 275862, 285862 and 295862 million tons respectively.

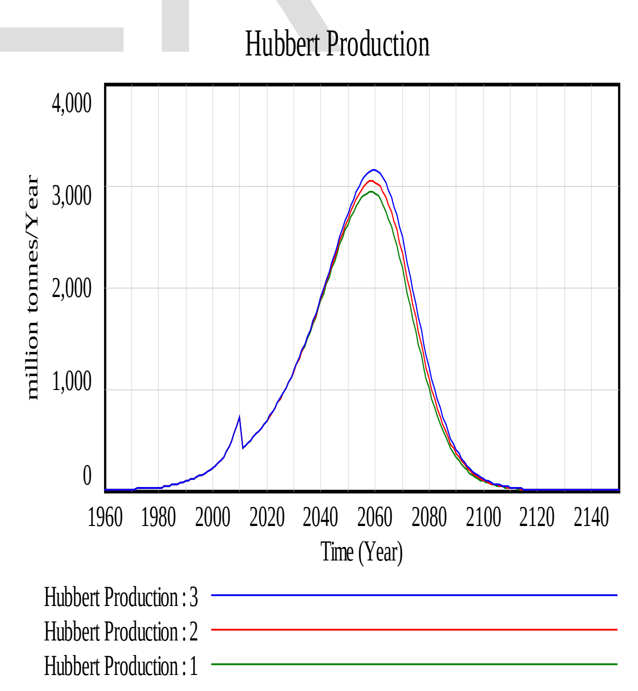

Fig.7. Hubbert Production at Different UR.

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TABLE 2
ILLUSTRATION OF HUBBERT PEAK UNDER DIFFERENT ULTIMATE RESERVES

Scenerio	Hubbert Peak Time(year)	Hubbert Peak Production(million tons/year)
UR=275862	2060	3145.96
UR=285862	2059	3040.86
UR=295862	2058	2933.87

The Hubbert's equation is highly dependent on the intrinsic growth rate. Here, this parameter is changed to perform a sensitivity analysis. Figure 8 and Table 3 show the results of this sensitivity analysis. Three different models have been implemented with different intrinsic growth rate. The three values are 0.062, 0.072 and 0.082. The results show that when the intrinsic growth rate varies from lower to higher amount, with the same ultimate reserves, the production peak will occur in lower time with higher production amount. In the Figure 8 the green, red and blue lines are indicating intrinsic growth rate 0.062, 0.072 and 0.082 respectively.

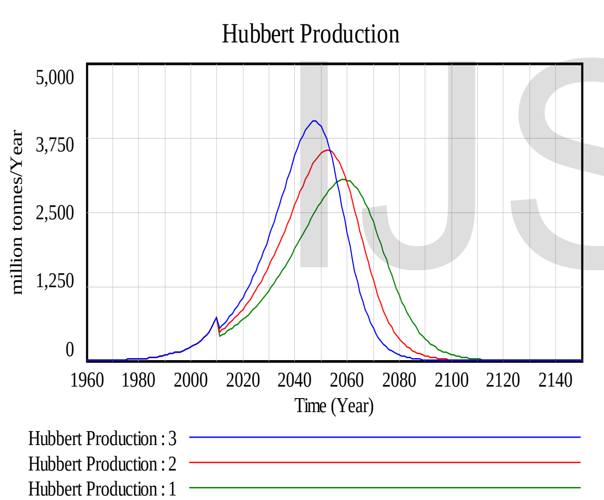

Fig.8. Hubbert Production at Different Intrinsic Growth Rates.

TABLE 3
ILLUSTRATION OF HUBBERT PEAK UNDER DIFFERENT INTRINSIC GROWTH RATE

Scenario	"Hubbert Peak Time(year)	Hubbert Peak Production(million tons/year)
a=0.062	2059	3040.86
a=0.072	2052	3529.75
a=0.082	2047	4018.65

4 EPILOGUE

India is the third largest producer of coal in the world. Coal is one of the primary sources of energy, accounting for about 67% of the total energy consumption in the country. India has the third largest reserves of coal in the world (approx. 285 billion tonnes.). Coal deposits in India occur mostly in thick seams and at shallow depths. Non-cooking coal reserves aggregate 242.25 billion tonnes (85 per cent) while coking coal reserves are 42.8 billion tonnes (the remaining 15 per cent). Indian coal has high ash content (15-45%) and low calorific value. With the present rate of around 0.8 million tons average daily coal extraction in the country, the reserves are likely to last over 100 years. The energy derived from coal in India is about twice that of energy derived from oil, as against the world, where energy derived from coal is about 30% lower than energy derived from oil. In export markets, coal remains the fastest growing fuel, driven by strong investment in coal-fired power stations in China and other developing economies. Considering these issues the question is when the Hubbert peak would happen about Australia's coal. In this study it is shown that the time is in the year 2059. Indian and international energy policy makers must be aware of this shortage of natural resources of India after approximately 2059. Further, within India, the share of coal in the energy mix is expected to decrease with the Renewable Energy target and a proposed emissions reduction target. Government and industry initiatives are expected to play important roles in accelerating the construction, demonstration and commercial deployment of large-scale integrated carbon capture and storage projects. This SD model gives the opportunity to include these policy changes and hence the sensitivity analysis, which helps the policy makers to make robust decisions.

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APPENDICES

	System Dynamics Model Equations
[01]	Actual Production=Coal+ Import +Export Units: million tonnes
[02]	Coal=Coal lookup(Time)*(1+Coal growth rate)^(Time-2010) Units: million tonnes
[03]	Coal growth rate=0.052 Units: 1/Year
[04]	Coal lookup([(0,0)-(2010,622.8)],(1980,125.9),(1981,142.9),(1982,149.4),(1983,155.9),(1984,183.9),(1985,189.9),(1986,208.4),(1987,210.7),(1988,226.4),(1989,233.8),(1990,247.6),(1991,269.9),(1992,279.5),(1993,288.1),(1994,300.8),(1995,320.6),(1996,314.9),(1997,338.1),(1998,343.1),(1999,356.3),(2000,370.1),(2001,388.7),(2002,395.6),(2003,420.5),(2004,446.7),(2005,473.3),(2006,500.2),(2007,531.5),(2008,568.5),(2009,613.4),(2010,622.8)) Units: million tonnes
[05]	Cumulative production= INTEG (Hubbert Production,1) Units: million tonnes
[06]	Export=Export lookup(Time)*(1+Export growth rate)^(Time-2010) Units: million tonnes
[07]	Export growth rate=0.232 Units: 1/Year
[08]	Export lookup([(0,0)-(2010,2.4)],(1980,0.12),(1981,0.13),(1982,0.2),(1983,0.09),(1984,0.1),(1985,0.24),(1986,0.15),(1987,0.26),(1988,0.21),(1989,0.22),(1990,0.11),(1991,0.1),(1992,0.14),(1993,0.11),(1994,0.2),(1995,0.76),(1996,0.54),(1997,0.6),(1998,0.87),(1999,1.28),(2000,1.43),(2001,2.1),(2002,1.68),(2003,2.01),(2004,1.6),(2005,2.37),(2006,1.8),(2007,1.9),(2008,3.3),(2009,2.78),(2010,2.4)) Units: million tonnes
[09]	FINAL TIME = 2150(The final time for the simulation.) Units: Year
[10]	Hubbert Production=IF THEN ELSE(Time<=2010,Actual Production,((1-(Cumulative production/Ultimate Reserve))*Cumulative production*"Intrinsic growth rate (coal)")) Units: million tonnes/Year
[11]	Import=Import lookup(Time)*(1+Import growth rate)^(Time-2010) Units: million tonnes
[12]	Import growth rate=0.283 Units: 1/Year
[13]	Import lookup([(0,0)-(2010,101.56)],(1980,0.36),(1981,0.72),(1982,1.52),(1983,0.51),(1984,0.64),(1985,2.24),(1986,2.31),(1987,3.27),(1988,4.08),(1989,4.86),(1990,5.57),(1991,7.24),(1992,7.16),(1993,8.02),(1994,9.86),(1995,11.07),(1996,15.89),(1997,20.66),(1998,19.96),(1999,24.29),(2000,25.74),(2001,25.17),(2002,28.11),(2003,25.99),(2004,34.53),(2005,45.42),(2006,52.65),(2007,59.57),(2008,67.11),(2009,83.17),(2010,101.56)) Units: million tonnes
[14]	INITIAL TIME = 1960 Units: Year The initial time for the simulation.
[15]	"Intrinsic growth rate (coal)"=0.062 Units: 1/Year
[16]	SAVEPER = TIME STEP Units: Year The frequency with which output is stored.
[17]	TIME STEP = 1 Units: Year The time step for the simulation.
[18]	Ultimate Reserve= INTEG (-Hubbert Production,285862) Units: million tonnes