ISSN 2229-5518

A Study on Hubbert Peak of Australia’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 Australia’s coal production. At first the peak determined with intrinsic growth rate 0.054 and ultimate reserve 84 billion tons. The Hubbert Peak for Australia’s coal production appears to be in 2044 with a value of 778.14 million tons. Later, sensitivity analysis has been made with different ultimate reserves and intrinsic growth rates.

Index Terms— Hubbert peak, coal, Australia, ultimate reserve, intrinsic rate.

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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 Australian economy. It plays a pivotal role out there. According to Australian coal association, in 2008 at $22.5 billion Australia is the largest single exporter, issued to generate 84% of Australia’s electricity and supports 130,000 employees [1][2]. Australia is the world’s largest exporter with about 30% of world total coal export trade and 4.6% of world consumption. Besides it is Australia’s largest commodity export, earning around $36 billion in 2009–10[3]. Australia’s success in world coal markets has been based on reliable and competitive supplies of high quality metallurgical and thermal coal. Coal is also a significant component of Australia’s domestic energy needs, accounting for around 84 per cent of Australian electricity generation in 2008–09. As a result prediction over coal production peak value and time has become the most important issue for Australia. 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:

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

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

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

Or

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

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.

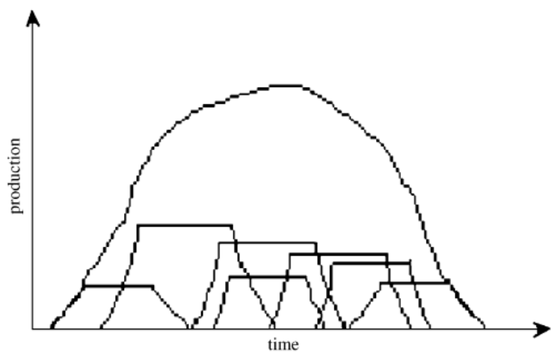

Fig. 1. Hubbert Curve.

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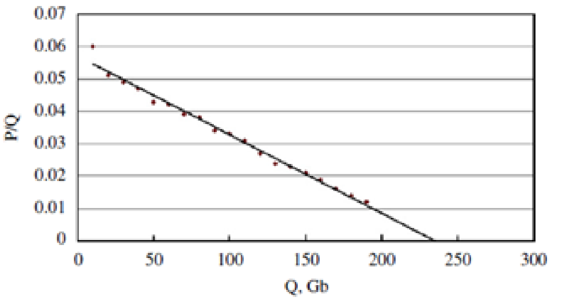

Fig. 2. Estimation of US production.

In this paper a system dynamics approach is used to examine the Hubbert peak of Australia's coal production. In section 2, the related literature of system dynamics with the reason why it is used in order to study the Australia's coal production outlook, is explained. In section 3 a system dynamics model of Australia's coal Hubbert peak is proposed. The model is simulated for 186 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 dynamicists 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.

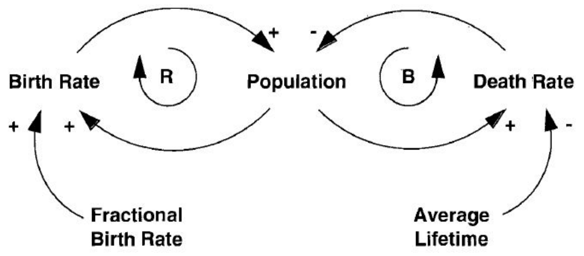

Fig. 3. Causal Loop Diagram.

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 assigned 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 counterclockwise along with its identifier.

A '+' link means that if the cause increases, the effect increases 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 decreases 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.

2.3 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 intrigration of information & 'rate' means- an increasing or decrecreasing amount of flow. A time factor is the main concern. Specifically, the differences between the level and the rate depend 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 AUSTRALIA'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.

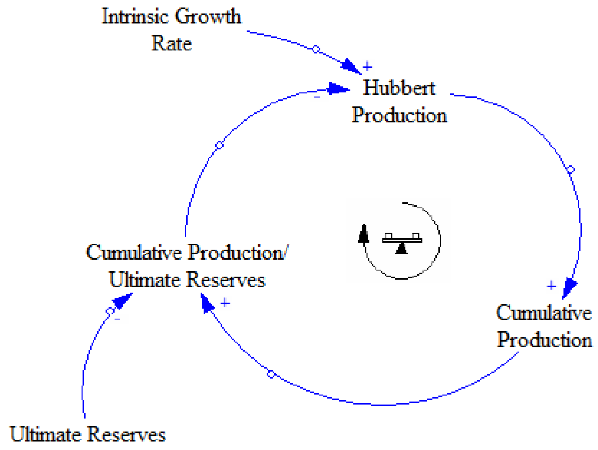

Fig. 4. Causal loop Diagram of Hubbert Peak.

A time horizon of 186 years is defined to show the history of Australia'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 Reserve does not have any inflows. This is because coal is created in geologic time. Thus, for all practical purposes, the total amount of oil 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 Australia's coal data, the intrinsic growth rate is 0.054. The historical data for Export and total coal (Black Coal & Brown Coal) are added with lookup variable which are named Export lookup and Total coal lookup respectively. The data is obtained from Australian commodity statistics 2009 & 2010 which is published by ABARES [7]. The model's equations are given in the Appendix.

The model shows that Australia coal production will reach its peak in 2044 with 778.141million tones/year as shown in figure 6. This model is free from all type of policies. In the Australian 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 Australia is 84.217 billion tons [9]. Here this paper considers recoverable black coal and brown coal resources in Australia 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 CO_2 emissions the use of coal is discouraged in Australia. Hence, no growth rate is used for the total coal amount which means no further increase of domestic consumption.

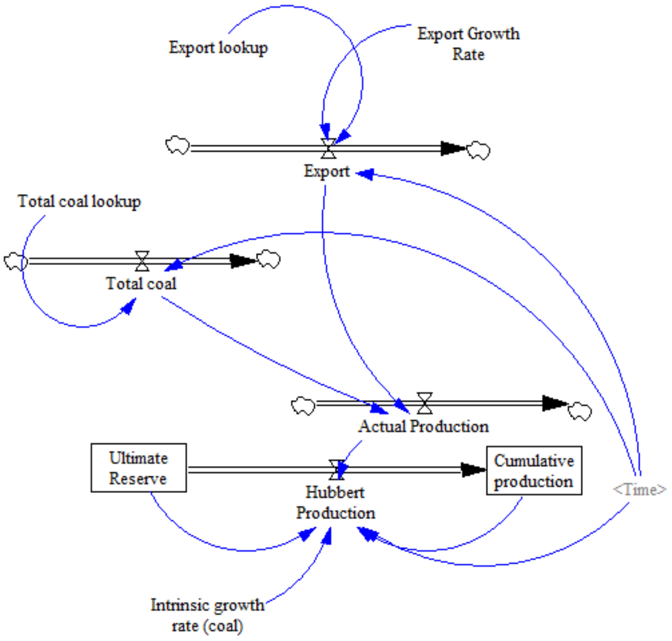

Fig: 5. Stock-flow Diagram of Hubbert Peak.

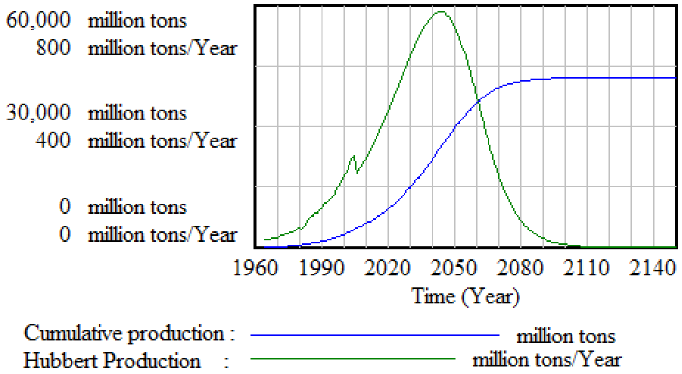

Fig. 6. The Stock-flow Diagram of Hubbert Peak.

TABLE 1
SIMULATION RESULTS OF HUBBERT PRODUCTION RATE AND CUMULATIVE PRODUCTION

Year	Hubbert Production (million tons/year)	Cumulative production(million tons)
2042	775.285	23309.5
2043	777.779	24084.8
2044	778.141(Peak)	24862.6
2045	776.272	25640.7
2046	772.094	26417

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 74000, 84000 and 94000 million tons. Figure 7 and Table 2 show the behavior of Australia'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 blue, green and black lines are indicating UR 74000, 84000 and 94000 million tons respectively.

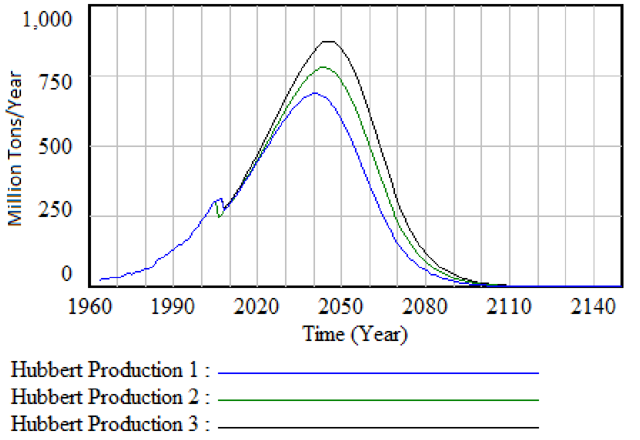

Fig. 7. Hubbert Production at Different UR.

TABLE 2
ILLUSTRATION OF HUBBERT PEAK UNDER DIFFERENT ULTIMATE RESERVES.

Scenario	Hubbert Peak Time (year)	Hubbert Peak Production (million tons/year)
UR= 74000	2041	685.477
UR= 84000	2044	778.141
UR= 94000	2046	870.607

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 0.054, 0.064 and 0.074. 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 blue, green and black lines are indicating intrinsic growth rate 0.054, 0.064 and 0.074 respectively.

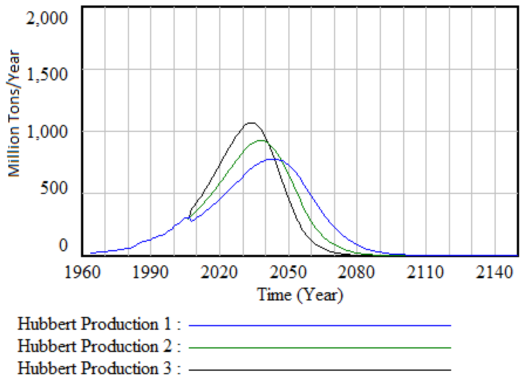

Fig 8: Hubbert Production at Different Intrinsic Growth Rates.

TABLE 3
ILLUSTRATION OF HUBBERT PEAK UNDER DIFFERENT INTRINSIC GROWTH RATES.

Scenario	Hubbert Peak Time (year)	Hubbert Peak Production (million tons/year)
a=0.054	2044	778.141
a=0.064	2038	922.357
a=0.074	2034	1066.44

4 EPILOGUE

Australia is the fourth largest producer, the largest exporter, and has the fourth largest reserves of coal in the world. Coal accounts for around three quarters of Australia's electricity generation, with coal-fired power stations located in every mainland state. 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 2044. Australian and international energy policy makers must be aware of this shortage of natural resources of Australia after approximately 2044. Further, within Australia, 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]	Export Export lookup(Time)*(1+Export Growth Rate)^(Time-2005)
[02]	Export Growth Rate 2.4%
[03]	Total coal Total coal lookup(Time)
[04]	Actual Production Total coal+Export
[05]	Ultimate Reserve INTEG(-Hubbert Prduction) Value used 84000 Million Tons.
[06]	Cumulative Production INTEG(-Hubbert Prduction)
[07]	Intrinsic growth Rate(coal) 0.054
[08]	Export lookup [(1964,20000)-(2005,300000)],(1964,5.94),(1965,8.87),(1966,8.04),(1967,10.48),(1968,14.41),(1969,17.97),(1970,18.96),(1971,21.85),(1972,25.83),(1973,28.39),(1974,32.42),(1975,30.43),(1976,35.37),(1977,37.91),(1978,38.28),(1979,43.16),(1980,47.25),(1981,46.12),(1982,54.65),(1983,64.33),(1984,86.1),(1985,90.3),(1986,97.7),(1987,102.1),(1988,97.66),(1989,104.58),(1990,113.37),(1991,123.3),(1992,129.18),(1993,129.06),(1994,136.24),(1995,138.55),(1996,145.75),(1997,162.61),(1998,169.41),(1999,175.78),(2000,193.5),(2001,197.87),(2002,207.74),(2003,218.43),(2004,231.31),(2005,231.3)
[09]	Total coal lookup [(1964,20000)-(2005,300000)],(1964,22.02),(1965,22.85),(1966,23.15),(1967,24.04),(1968,24.71),(1969,25.57),(1970,24.96),(1971,25.49),(1972,27.39),(1973,27.68),(1974,30.19),(1975,29.45),(1976,32.19),(1977,32.56),(1978,33.43),(1979,35.62),(1980,37.71),(1981,36.79),(1982,37.29),(1983,38.64),(1984,40.67),(1985,42.56),(1986,44.07),(1987,46.01),(1988,49.87),(1989,50.68),(1990,50.92),(1991,52.81),(1992,52.94),(1993,54.18),(1994,55.36),(1995,57.41),(1996,57.88),(1997,61.26),(1998,61.64),(1999,61.3),(2000,64.13),(2001,66.16),(2002,66.34),(2003,69.24),(2004,71.29),(2005,71.58)
[10]	Hubbert Production IF THEN ELSE(Time<=2005,Actual Production,((1-(Cumulative production/Ultimate Reserve))*Cumulative production*"Intrinsic growth rate (coal)"))
[11]	Time Time Step = 1year