PROJECTION OF WORLD FOSSIL FUEL PRODUCTION WITH SUPPLY AND DEMAND INTERACTIONS

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Statement of Originality

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying subject to the provisions of the Copyright Act 1968

Acknowledgment of Authorship

I hereby certify that the work embodied in this thesis contains published papers of which I am a joint author. I have included as part of the thesis a written statement, endorsed by my supervisor, attesting to my contribution to the joint publications:

During the writing of this thesis I have received advice, guidance, and engineering based assistance from my supervisor. The assistance has been within the scope of normal supervisor-student relations. Apart from their help, this thesis has been all my own work. Some of the information in this thesis are contained in papers Mohr and Evan (2009a, 2009b), written jointly with my supervisor.

Steve H. Mohr

Professor Geoffrey M. Evans

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Publications

S. H. Mohr and G. M. Evans, “Mathematical model forecasts year conventional oil will peak”, *Oil and Gas Journal* **105**(17), pg. 45–46, 48–50, 2007.

S. H. Mohr and G. M. Evans, “Models provide insight on North America gas future”, *Oil and Gas Journal* **105**(25), pg. 51–52, 54–55, 2007.

S. H. Mohr and G. M. Evans, “Model proposed for world conventional, unconventional gas”, *Oil and Gas Journal*, **105**(47), pg. 46–51, 2007.

S. H. Mohr and G. M. Evans, “Peak Oil: Testing Hubbert’s Curve via Theoretical Modeling”, *Natural Resources Research*, **17**(1), pg 1–11, 2008.

S. H. Mohr and G. M. Evans, “Modelling Fossil Fuels Production to 2100”, *Chemeca Conference*, Newcastle, Australia, October, 2008.

S. H. Mohr and G. M. Evans, “Demand-Supply Interaction on Future Mining Resource Production: The Coal Model”, *CSRP Conference*, Brisbane, Australia, November, 2008.

S. H. Mohr and G. M. Evans, “An Empirical Method to Make Oil Production Models Tolerant to Anomalies”, *Natural Resources Research*, **18**(1), pg 1–5, 2009.

S. H. Mohr and G. M. Evans, “Forecasting coal production until 2100”, *Fuel*, **88**(11), pg 2059–2067, 2009.

S. H. Mohr and G. M. Evans, “Predicting Unconventional Oil Production for the next 200 years”, *Energy Policy*, **38**(1), pg 265–276, 2010.

Contents

List of Symbols

Constants		unit
A_n	Weighting factor for the n-th fossil fuel e.g. Eq. 3.7.7	(-)
b	y-intercept of the regression line e.g. Eq. 2.2.6	(-)
c	Constant e.g. Eq. 2.2.2	(-)
D_f	Final year of a disruption e.g. Eq. 3.5.1	(y)
$\tilde{D}_H$	Maximum achievable per capita demand e.g. Eq. 3.6.2	(EJ/y)
D_n	The percent change in the number of well or mines during a disruption e.g. Eq. 3.5.1	(-)
D_s	Start year of a disruption e.g. Eq. 3.5.1	(y)
f_{C_H}	The highest possible fraction of fossil fuel demand for coal e.g. Eq. 3.6.5	(-)
f_{C_L}	The lowest possible fraction of fossil fuel demand for coal e.g. Eq. 3.6.5	(-)
f_{G_H}	The highest possible fraction of fossil fuel demand for natural gas e.g. Eq. 3.6.4	(-)
f_{G_L}	The lowest possible fraction of fossil fuel demand for natural gas e.g. Eq. 3.6.4	(-)
$\tilde{F}_P$	Proportionality constant of the max prod. relative to the URR of a field e.g. Eq. 3.2.4	(y^{-1})
F_{P_i}	Maximum production of the i-th field e.g. Eq. 3.2.1	(EJ/y)
$\mathbb{G}_L$	The minimum driver necessary to cause mines to upgrade e.g. Eq. 3.7.12	(-)
$\mathcal{G}_L$	The minimum driver necessary to put more oil and gas regions on-line e.g. Eq. 3.7.9	(-)
k_D	Constant for the demand e.g. Eq. 3.7.5	(-)
k_F	Constant for the number of fields e.g. Eq. 3.7.7	(-)
k_M	Constant for the number of mines e.g. Eq. 3.7.8	(-)
k_R	Number of oil and gas regions constant e.g. Eq. 3.7.11	(-)
k_U	Constant for upgrades e.g. Eq. 3.7.13	(-)
L_{F_i}	Life of the i-th Field e.g. Eq. 3.2.3	(y)
L_H	Highest operating life of a mine e.g. Eq. 3.4.1	(y)
L_L	Lowest operating life of a mine e.g. Eq. 3.4.1	(y)
L_{M_i}	Life of the i-th mine e.g. Eq. 3.4.3	(y)
m	Gradient of the regression line e.g. Eq. 2.2.6	(-)
M_H	Highest maximum production of a mine e.g. Eq. 3.4.2	(EJ/y)
M_L	Lowest maximum production of a mine e.g. Eq. 3.4.2	(EJ/y)
M_{P_i}	Maximum production of the i-th mine e.g. Eq. 3.4.3	(EJ/y)
n_{F_T}	The total number of fields in an oil or gas region e.g. Eq. 3.2.7	(-)
n_{R_T}	The total number of oil or gas regions e.g. Eq. 3.3.2	(-)
n_{W_T}	Total number of wells e.g. Eq. 2.3.4	(-)
p_H	The maximum achievable population e.g. Eq. 3.6.1	(-)
p_L	The minimum achievable population e.g. Eq. 3.6.1	(-)

P_0	Initial production e.g. Eq. 2.3.3	(EJ/y)
P_p	Peak production e.g. Eq. 2.2.7	(EJ/y)
$\breve{Q}$	A constant relating to the estimated amount of the URR that is exploited e.g. Eq. 3.5.4	(EJ)
$\tilde{Q}_r$	Proportionality constant of Q_{r_i} relative to the URR of a field e.g. Eq. 3.2.5	(-)
Q_{r_i}	Remaining URR in the i-th field when production begins to decline e.g. Eq. 3.2.1	(EJ)
Q_{R_T}	The ultimately recoverable resources in an oil or gas region e.g. Eq. 3.2.7	(EJ)
$Q_{R_{T_i}}$	The ultimately recoverable resources in the i-th oil or gas region e.g. Eq. 3.3.5	(EJ)
Q_T	Ultimately recoverable resources e.g. Eq. 2.2.1	(EJ)
Q_{T_i}	The URR in the i-th mine or field e.g. Eq. 3.2.8	(EJ)
$\mathcal{Q}_T$	Ultimately recoverable reserves for Bass model e.g. Eq. 2.2.11	(EJ)
r	Rate constant e.g. Eq. 2.2.1	(y^{-1})
r_D	The rate constant for per capita demand e.g. Eq. 3.6.2	(y^{-1})
r_{dec}	Rate of decrease e.g. Eq. H.1.2	(t^{-1})
r_ϵ	Rate of URR constant e.g. Eq. 3.3.4	(-)
r_{f_C}	Rate constant for coal fraction e.g. Eq. 3.6.5	(y^{-1})
r_{f_G}	Rate constant for natural gas fraction e.g. Eq. 3.6.4	(y^{-1})
r_F	Rate of fields constants e.g. Eq. 3.2.7	(-)
r_{inc}	Rate of increase e.g. Eq. H.1.2	(y^{-1})
r_m	Rate constant for population e.g. Eq. 3.6.1	(y^{-1})
r_Q	Rate constant for the exploitable URR in a field e.g. Eq. 3.2.9	(-)
r_{Q_T}	Rate constant for the exploitable URR in a mine e.g. Eq. 3.4.6	(-)
r_t	Rate constant for technology e.g. Eq. 3.4.1	(y^{-1})
$\mathcal{R}^2$	Coefficient of determination	(-)
S	Asymmetry constant e.g. Eq. H.1.1	(-)
t_d	Disruption year e.g. Eq. 2.2.16	(y)
t_D	Time constant for per capita demand e.g. Eq. 3.6.2	(y)
t_{f_C}	Time constant for fraction of coal e.g. Eq. 3.6.5	(-)
t_{f_G}	Time constant for fraction of natural gas e.g. Eq. 3.6.4	(y)
t_F	Time for a field to reach maximum production e.g. Eq. 3.2.1	(y)
t_m	Population midpoint year e.g. Eq. 3.6.1	(y)
t_p	Peak year e.g. Eq. 2.2.3	(y)
t_{r_i}	The year the production of a field begins to decrease e.g. Eq. 3.2.1	(y)
t_t	Mid year for the technology e.g. Eq. 3.4.1	(y)
Y_{F_i}	Year the i-th field starts e.g. Eq. 3.2.1	(y)
Y_{M_i}	Year the i-th mine starts e.g. Eq. 3.4.3	(y)
Y_s	Start year for a mining region or an oil or gas region e.g. Eq. 3.4.6	(y)

Subscripts

0	Initial e.g. Eq. 2.3.3	(-)
A	API e.g. Eq. 1.2.1	(-)

C	Coal e.g. Eq. 3.6.3	(-)
d	Disruption e.g. Eq. 2.2.16	(-)
e	Estimated exploited e.g. Eq. 3.4.6	(-)
E	Exploited e.g. Eq. 3.2.8	(-)
ϵ	Quasi-exploited e.g. Eq. 3.3.2	(-)
f	Final year e.g. Eq. 3.5.1	(-)
f_C	Coal fraction e.g. Eq. 3.6.5	(-)
f_G	Natural gas fraction e.g. Eq. 3.6.4	(-)
F	Field e.g. Eq. 3.2.1	(-)
G	Natural gas e.g. Eq. 3.6.3	(-)
H	Highest e.g. Eq. 3.4.1	(-)
i	i-th e.g. Eq. 3.4.4	(-)
j	j-th e.g. Eq. 3.3.1	(-)
L	Lowest e.g. Eq. 3.4.1	(-)
m	Population e.g. Eq. 3.6.1	(-)
M	Mine e.g. Eq. 3.4.1	(-)
n	Number e.g. Eq. 3.5.1	(-)
n	The n-th fossil fuel e.g. Eq. 3.7.7	(-)
O	Oil e.g. Eq. 3.6.3	(-)
p	Peak e.g. Eq. 2.2.3	(-)
P	Production e.g. Eq. 3.4.2	(-)
Q	Cumulative e.g. Eq. 3.2.9	(-)
Q_T	Ultimately recoverable resources e.g. Eq. 3.4.6	(-)
r	Decline e.g. Eq. 3.2.1	(-)
R	Oil or gas region e.g. Eq. 3.2.6	(-)
s	Start year e.g. Eq. 3.2.1	(-)
S	Specific - relative to water e.g. Eq. 1.2.1	(-)
t	Technology e.g. Eq. 3.4.1	(-)
T	Total e.g. Eq. 2.2.1	(-)
W	Well e.g. Eq. 2.3.4	(-)

Functions

$d(t)$	Discoveries e.g. Eq. 2.4.1	(EJ)
$\breve{D}(t)$	Potential demand e.g. Eq. 3.7.5	(EJ/y)
$D_C(t)$	Demand for coal e.g. Eq. 3.6.6	(EJ/y)
$\tilde{D}_C(t)$	Per capita demand for total fossil fuel used by coal e.g. Eq. 3.6.6	(EJ/y)
$D_G(t)$	Demand for natural gas e.g. Eq. 3.6.7	(EJ/y)
$\tilde{D}_G(t)$	Per capita demand for total fossil fuel used by natural gas e.g. Eq. 3.6.7	(EJ/y)
$\tilde{D}_i(t)$	Per capita demand for total fossil fuel used by fuel i e.g. Eq. 3.6.2	(EJ/y)
$D_O(t)$	Demand for oil e.g. Eq. 3.6.8	(EJ/y)

$\tilde{D}_O(t)$	Per capita demand for total fossil fuel used by oil e.g. Eq. 3.6.8	(EJ/y)
$D_T(t)$	Demand for all fossil fuels e.g. Eq. 3.6.9	(EJ/y)
$\tilde{D}_T(t)$	Per capita demand for total fossil fuel e.g. Eq. 3.6.9	(EJ/y)
$f_C(t)$	Fraction of coal e.g. Eq. 3.6.3	(-)
$f_G(t)$	Fraction of natural gas e.g. Eq. 3.6.3	(-)
$f_i(t)$	Fraction of fossil fuel demand for fuel i e.g. Eq. 3.7.5	(-)
$f_O(t)$	Fraction of oil e.g. Eq. 3.6.3	(-)
$g(t)$	GDP per capita e.g. Eq. 2.3.2	(-)
$G_C(t)$	Coal supply and demand driver e.g. Eq. 3.7.1	(-)
$G_T(t)$	Fossil fuel supply and demand driver e.g. Eq. 3.7.4	(-)
$G_G(t)$	Natural gas supply and demand driver e.g. Eq. 3.7.2	(-)
$G_i(t)$	Driver for fuel i e.g. Eq. 3.7.5	(-)
$G_O(t)$	Oil supply and demand driver e.g. Eq. 3.7.3	(-)
$\mathcal{G}_i(t)$	The oil and gas regions driver e.g. Eq. 3.7.9	(-)
$\mathbb{G}_i(t)$	The upgraded mines driver e.g. Eq. 3.7.12	(-)
$H(x)$	Heavy side step function e.g. Eq. 2.2.16	(-)
$L_F(t)$	Operating life of a field that commenced in year t e.g. Eq. 3.2.3	(y)
$L_M(t)$	Operating life of a mine that commenced in year t e.g. Eq. 3.4.1	(y)
$M_P(t)$	Maximum production of a mine that commenced in year t e.g. Eq. 3.4.2	(EJ/y)
$n(t)$	The number of mines or fields e.g. Eq. 3.5.1	(-)
$n_F(t)$	The number of fields on-line in an oil or gas region e.g. Eq. 3.2.6	(-)
$\breve{n}_F(t)$	The estimated number of fields on-line e.g. Eq. 3.5.2	(-)
$n_M(t)$	The number of mines e.g. Eq. 3.4.4	(-)
$n_R(t)$	Number of oil or gas regions on-line e.g. Eq. 3.3.1	(-)
$n_U(t)$	Number of mines being upgraded e.g. Eq. 3.7.13	(-)
$n_W(t)$	Number of wells e.g. Eq. 2.3.4	(-)
$p(t)$	Population e.g. Eq. 2.3.2	(-)
$P(t)$	Production e.g. Eq. 2.3.2	(EJ/y)
$P_C(t)$	Total coal production e.g. Eq. 3.7.1	(EJ/y)
$P_T(t)$	Total fossil fuel production e.g. Eq. 3.7.4	(EJ/y)
$P_{F_i}(t)$	Production from the i-th field e.g. Eq. 3.2.1	(EJ/y)
$P_G(t)$	Total natural gas production e.g. Eq. 3.7.2	(EJ/y)
$P_{M_i}(t)$	Production from the i-th mine e.g. Eq. 3.4.4	(EJ/y)
$P_O(t)$	Total oil production e.g. Eq. 3.7.3	(EJ/y)
$P_R(t)$	Production from an oil or gas region e.g. Eq. 3.2.6	(EJ/y)
$P_{R_j}(t)$	Production in the j-th oil or gas region e.g. Eq. 3.3.1	(EJ/y)
$Q(t)$	Cumulative production e.g. Eq. 2.2.1	(EJ)
$Q_e(t)$	The estimated amount of the URR that is exploited e.g. Eq. 3.4.6	(EJ)
$Q_E(t)$	The amount of the URR that is actively exploited e.g. Eq. 3.2.8	(EJ)

$Q_\epsilon(i)$	Ultimately recoverable resources in the first i oil or gas regions e.g. Eq. 3.3.3	(EJ)
$\mathcal{Q}(t)$	Cumulative production for Bass model e.g. Eq. 2.2.11	(EJ)
$R(t)$	Reserves e.g. Eq. 2.3.2	(EJ)
$T(t)$	Technology function e.g. Eq. 2.3.2	(-)
$v(t)$	Variation function e.g. Eq. 2.3.1	(-)
$x(t)$	Intervention function e.g. Eq. 2.2.11	(-)
$y(x)$	Regression line e.g. Eq. 2.2.6	(-)

Greek Letters

α	Generic constant e.g. Eq. 3.4.7	(-)
$\phi(t)$	Probability of finding oil e.g. Eq. 2.4.1	(-)
γ_{f_C}	Asymmetry constant for coal fraction e.g. Eq. 3.6.5	(-)
γ_m	Asymmetry constant for population e.g. Eq. 3.6.1	(-)
μ	mean	(-)
ρ	Density e.g. Eq. 1.2.1	(^{o},-)
σ	Standard deviation	(-)

Variables

i	Number e.g. Eq. 3.3.2	(-)
t	Time e.g. Eq. 2.2.1	(y)
x	Generic variable e.g. Eq. 2.2.6	(-)

Abstract

Historically, fossil fuels have been vital for our global energy needs. However climate change is prompting renewed interest in the role of fossil fuel production for our energy needs. In order to appropriately plan for our future energy needs, a new detailed model of fossil fuel supply is required. It is critical to know if fossil fuels will still be able to supply most of our energy requirements and meet the ever increasing energy demand in the future. Answering these questions is critical in order to identify potential periods of energy shortages; so that alternative energy resources can be utilised in a timely way. The aim of this study was to develop a model to predict fossil fuel production for the long term based on historical production data, projected demand, and assumed ultimately recoverable reserves for coal, gas and oil. Climate change is an important issue confronting society, and it is hoped that the work contained in this thesis will aid climate change modeling by focusing attention to realistic fossil fuel production projections.

The modelling applied an algorithm-based approach to predict both supply and demand for coal, gas, oil and total fossil fuel resources. Total fossil fuel demand was calculated globally, based on world population and per capita demand; while production was calculated on a country-by-country basis and summed to obtain global production. Notably, production over the lifetime of a fuel source was not assumed to be symmetrical about a peak value like that depicted by a Hubbert curve. Separate production models were developed for mining (coal and unconventional oil) and field (gas and conventional oil) operations, which reflected the basic differences in extraction and processing techniques. Both of these models included a number of parameters that were fitted to historical production data, including: (1) coal for New South Wales, Australia; (2) gas from the North Sea, UK; and (3) oil from the North Sea, UK, and individual state data from the USA.

The combined supply and demand model included the capability that demand and production could be influenced by each other, i.e. if production could not meet demand then future demand for that energy source was reduced. In this study, three options were considered. Firstly, the STATIC option resulted in demand and production acting independently of each other at all times. Secondly, the DYNAMIC option allowed both total demand and total production to change from the STATIC situation when there was a difference between the two. Finally, the INDEPENDENTLY DYNAMIC option was an extension to the DYNAMIC situation, but treated each fuel source individually when applying the supply and demand interaction, with both demand and production being able to vary.

The model required estimates of Ultimately Recoverable Resources (URR) for coal, gas and oil, where the following definitions were used for each resource: (1) Coal: anthracite - lignite; (2) Gas: conventional and unconventional (tight, shale and coal bed methane); (3) Oil: conventional (API>10^{o}) and unconventional (natural bitumen, extra heavy oil, oil shale). Following a critical review of the literature, included in this study, three cases were adopted. CASE *1* and CASE *3* being lowest and highest recent estimates, respectively, and CASE *2* being author's best guess based on the information available. The URR values for CASE *2* were, total (60,800 EJ), coal (19,350 EJ), gas (17,680 EJ) and oil (23,780 EJ).

The supply and demand model was used to obtain future predictions for individual and total fossil fuel productions for a number of different scenarios, including CASE *1*, CASE *2* and CASE *3* and STATIC, DYNAMIC and INDEPENDENTLY DYNAMIC supply and demand interaction options. The following results were obtained:

Coal: For CASE *2*, peak production year remained constant at 2019 for STATIC, DYNAMIC and INDEPENDENTLY DYNAMIC options, with peak production varying only marginally between 212–214 EJ/y. Similarly, for CASE *1*, peak production year was the same at 2014 for all three demand-production interaction options. However, for CASE *3*, there was some variation in the peak production year at 2020, 2019 and 2030 for STATIC, DYNAMIC and INDEPENDENTLY DYNAMIC options respectively. Of interest also, was the projected peak in Chinese production, accounting for well over a third of the total production, of between 2010 and 2018, which compares with reported literature values in the range 2015–2033.

Gas: For CASE *2*, peak production year varied from 2028, 2047 and 3034 for STATIC, DYNAMIC and INDEPENDENTLY DYNAMIC options, respectively. The corresponding peak production outputs were 145, 157 and 143 EJ/y. For CASE *1*, peak production year varied from 2019, 2033 and 2026, respectively, for the production interaction options. For CASE *3*, the peak year range was much narrower, varying between 2060 and 2062. The overall range of between 2019–2062, was much wider than that reported in most of the literature of 2020 $\pm$ 10 years. While it was found that the production of unconventional gas was considerable it was unable to mitigate conventional gas peaking.

Oil: For CASE *2*, peak production year remained almost constant at 2011-12 for STATIC, DYNAMIC and INDEPENDENTLY DYNAMIC options, with peak production varying only marginally between 179–188 EJ/y. Similarly, for CASE *1*, peak production year was the same at 2005 for all three supply and demand interaction options. For CASE *3*, peak production year varied only slightly at 2019, 2011 and 2016 for STATIC, DYNAMIC and INDEPENDENTLY DYNAMIC options, respectively. The important outcome was that for all scenarios the maximum peak year was 2019.

Combined fossil fuels: For CASE *2*, peak production year remained almost constant at 2016–18 for STATIC, DYNAMIC and INDEPENDENTLY DYNAMIC options, with peak production varying only marginally between 509–525 EJ/y. Similarly, for CASE *1*, peak production year was essentially same at 2012–13 for all three supply and demand interaction options. For CASE *3*, peak production year varied from 2021 to 2029 across the three supply and demand options. In all scenarios it was found that natural gas offers the biggest future potential, and not coal.

It is important to be caution about the long term future projections. In particular wars, natural disasters, economic depressions, new technologies, presumably will occur in the future and have not been accounted for in the projection. The long term projections presented in the thesis are to show the reader what is possible and plausible.

The thesis predictions were compared to predictions made by the well-known Hubbert model, which is based on a symmetrical production profile about a peak year. It was found that the resultant Hubbert curves were generally in good agreement with total fossil fuel, coal and natural gas production predictions. This result was perhaps not surprising, given that the asymmetry constant, defined the cumulative production in the peak year divided by the URR peak production, was mostly in the range 0.4–0.6; where a value of 0.5 indicates symmetry. There was a disparity between the Hubbert curve and model predictions for unconventional oil, which was due to the external disruptions in production.

Fossil fuels are currently an essential component in the global economy and the growth of the human population. The fossil fuel production projections from this study suggest that many of the IPCC fossil fuel projections appear overly optimistic. Based on the assumed URR values, it is predicted that global fossil fuel production will peak before 2030. For this reason, it is imperative that appropriate action be taken as early as possible to mitigate the effects of fossil fuel decline, to avoid energy shortages in the near future.