

# Contents

<b>Contents</b>	<b>I</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Background . . . . .	1
1.1.1 Prudence and precautionary saving . . . . .	1
1.1.2 Natural resource uncertainty . . . . .	6
1.1.3 Climatic uncertainty . . . . .	7
1.1.4 Perturbation methods . . . . .	10
1.2 Synopsis and layout . . . . .	15
1.3 Symbols and conventions . . . . .	17
1.4 Publications . . . . .	17
<b>2 Precautionary saving for resource price uncertainty</b>	<b>19</b>
2.1 Introduction . . . . .	20
2.2 Principles of managing volatile oil windfalls . . . . .	22
2.2.1 Three types of funds for managing volatile oil windfalls . . . . .	22
2.2.2 What assets should the funds invest in? . . . . .	24
2.2.3 Hedging against volatile oil prices . . . . .	24
2.2.4 General economic policy . . . . .	25
2.3 Theory of managing volatile oil windfalls . . . . .	25
2.3.1 No capital scarcity: intergenerational and liquidity funds . . . . .	29
2.3.2 Capital scarcity: investing to invest . . . . .	31
2.4 Three different windfalls . . . . .	32
2.4.1 Norway: declining oil windfall, no capital scarcity . . . . .	32
2.4.2 Iraq: huge and long-lasting oil windfalls . . . . .	35
2.4.3 Ghana: temporary, small oil windfall . . . . .	35
2.5 Calibration . . . . .	37
2.5.1 Population growth and technical progress . . . . .	38
2.5.2 Stochastic dynamics of the oil price . . . . .	38
2.5.3 Interest rates and interest premium on national debt . . . . .	39
2.5.4 Public investment: productivity and inefficiency . . . . .	41
2.6 Estimates of intergenerational and liquidity funds . . . . .	42
2.6.1 Norway . . . . .	42

2.6.2	Dominance of Iraq’s liquidity buffer . . . . .	45
2.6.3	Small intergenerational and liquidity buffers for Ghana . . . . .	47
2.7	Capital strategy and investing to invest strategy for Ghana . . . . .	48
2.8	Conclusions . . . . .	49
<b>3</b>	<b>Case study: resource revenues in Alberta</b>	<b>55</b>
3.1	Introduction . . . . .	56
3.2	How to build an intergenerational fund . . . . .	58
3.2.1	Policy implications . . . . .	59
3.2.2	Other choices of discount rates . . . . .	60
3.3	Oil price volatility and the case for a liquidity fund . . . . .	60
3.4	Data and assumptions for Alberta . . . . .	61
3.4.1	Extraction rates and reserve estimates . . . . .	61
3.4.2	Government resource rents . . . . .	62
3.4.3	Return on the fund and general economic trends . . . . .	63
3.5	Optimal intergenerational and liquidity funds for Alberta . . . . .	64
3.5.1	Benchmark estimates and the effects of prudence . . . . .	64
3.5.2	Comparison with the spend-all and bird-in-hand rules . . . . .	66
3.6	Sensitivity analysis . . . . .	67
3.6.1	Alternative production scenarios . . . . .	68
3.6.2	Effects of a lower real return on assets . . . . .	68
3.6.3	Correlation between gas and oil prices . . . . .	69
3.6.4	The plunge in oil price . . . . .	69
3.7	Conclusions and policy implications . . . . .	71
<b>4</b>	<b>Asset allocation and extraction for resource SWFs</b>	<b>75</b>
4.1	Introduction . . . . .	76
4.2	The model . . . . .	77
4.3	Complete markets and a given path of oil extraction . . . . .	79
4.3.1	Asset allocation: leverage and hedging demands . . . . .	80
4.3.2	Consumption rules and precautionary saving . . . . .	82
4.3.3	Intergenerational equity and risk aversion: EZ preferences . . . . .	83
4.4	Investment restrictions and a given path of oil extraction . . . . .	84
4.4.1	Additional precautionary saving . . . . .	84
4.4.2	Stylized illustration of oil-CAPM model . . . . .	85
4.5	Portfolio allocation and spending with endogenous oil extraction . . . . .	88
4.5.1	Optimal rates of oil extraction . . . . .	88
4.5.2	SFWs with endogenous rates of oil extraction . . . . .	90
4.6	Policy implications: Norway’s Government Pension Fund Global . . . . .	92
4.7	Conclusions . . . . .	94

<b>5</b>	<b>The risk-adjusted carbon price</b>	<b>97</b>
5.1	Introduction . . . . .	98
5.2	A DSGE model of global warming and the economy . . . . .	101
5.3	Asymptotic solutions for the optimal risk-adjusted price of carbon	105
5.3.1	Transforming to non-dimensional form and scaling . . . . .	106
5.3.2	Perturbation expansion . . . . .	106
5.3.3	Perturbation solutions . . . . .	107
5.4	The optimal risk-adjusted SCC: leading-order effects of uncertainty	109
5.4.1	The optimal SCC in the absence of uncertainty . . . . .	110
5.4.2	Economic growth uncertainty and the climate beta . . . . .	110
5.4.3	Climate and damage uncertainties . . . . .	111
5.4.4	Climate betas: . . . . .	112
5.4.5	Special case: logarithmic preferences . . . . .	113
5.5	Calibration . . . . .	113
5.6	Quantification of effects on optimal SCC . . . . .	115
5.6.1	Economic determinants of the optimal carbon price . . . . .	116
5.6.2	Climate betas . . . . .	118
5.6.3	Comparison with other calibrations . . . . .	118
5.6.4	Accuracy of the tractable rule . . . . .	120
5.7	Conclusions . . . . .	120
<b>6</b>	<b>Discussion</b>	<b>123</b>
6.1	Non-resource and non-climatic uncertainty . . . . .	124
6.2	Uncertain natural resource reserves and stranded assets . . . . .	126
6.3	Climate uncertainty and catastrophes . . . . .	127
6.4	Conclusions . . . . .	131
	<b>Summary</b>	<b>133</b>
	<b>Samenvatting</b>	<b>137</b>
	<b>Biography</b>	<b>141</b>
	<b>Acknowledgements</b>	<b>143</b>
	<b>Bibliography</b>	<b>145</b>
<b>A</b>	<b>Appendix to Chapter 3: Model equations</b>	<b>159</b>
<b>B</b>	<b>Appendix to Chapter 3: Detailed description of data</b>	<b>161</b>
B.1	Real interest rates . . . . .	161
B.2	Estimates of reserve stocks . . . . .	162
B.3	Official projections of extraction rates . . . . .	163
B.4	Extraction costs . . . . .	163
B.5	Price processes . . . . .	165

B.6	Economic and population growth . . . . .	167
B.7	Historical series of government resources . . . . .	169
B.8	Initial size of the fund . . . . .	169
<b>C</b>	<b>Appendix to Chapter 4</b>	<b>171</b>
C.1	Valuing oil with exogenous oil extraction . . . . .	171
C.2	Asset allocation with exogenous oil extraction . . . . .	173
C.3	Optimal consumption with exogenous oil extraction . . . . .	174
C.4	Complete markets and exogenous oil paths: EZ preferences . . . . .	176
C.5	Endogenous oil extraction . . . . .	176
C.6	Asset allocation with endogenous oil extraction . . . . .	179
<b>D</b>	<b>Appendix to Chapter 5</b>	<b>181</b>
D.1	Risk-adjusted carbon price with convex reduced-form damages . . . . .	181
D.2	Transformation to non-dimensional form . . . . .	184
D.3	Derivation of zeroth-order solution . . . . .	185
D.4	Derivation of first-order solution . . . . .	187
	D.4.1 Solution to multi-variate Ornstein-Uhlenbeck process . . . . .	187
	D.4.2 Evolution equations for $\hat{K}$ and $\hat{E}$ . . . . .	188
	D.4.3 The Hamilton-Jacobi-Bellman equation . . . . .	189
D.5	Leading-order effects of uncertainty . . . . .	194
	D.5.1 Carbon stock dynamics . . . . .	194
	D.5.2 Leading-order forcing . . . . .	195
	D.5.3 Leading-order solution . . . . .	201
D.6	Calibration . . . . .	202
	D.6.1 Asset returns, risk aversion and intertemporal substitution . . . . .	202
	D.6.2 Production function parameters . . . . .	203
	D.6.3 Atmospheric carbon stock and uncertainty . . . . .	204
	D.6.4 Curvature of the temperature-carbon stock relationship . . . . .	206
	D.6.5 Climate damages and climate damage uncertainty . . . . .	207
	D.6.6 Climate sensitivity and uncertainty . . . . .	209
D.7	Accuracy of Results 2 and 2' . . . . .	214