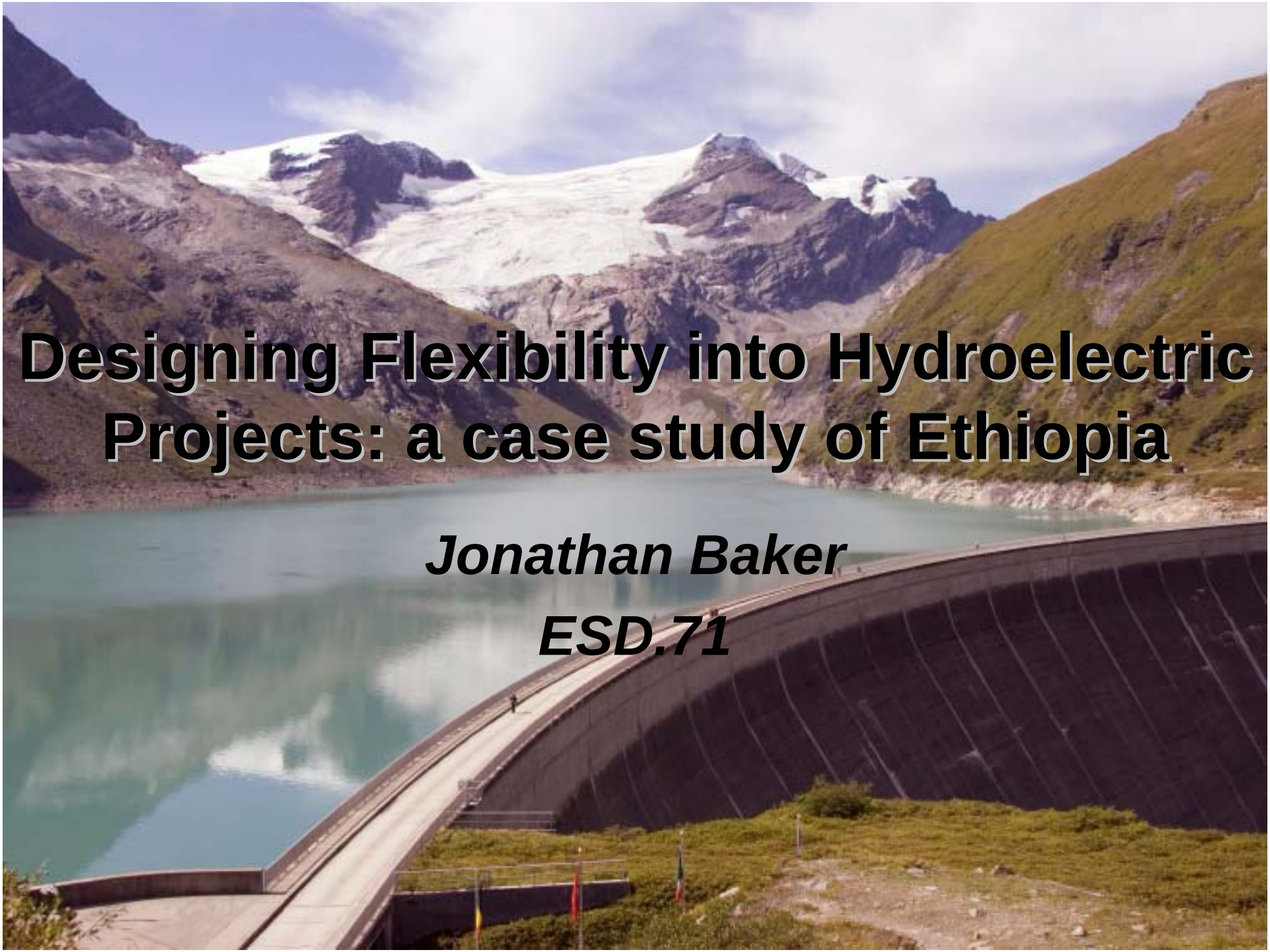
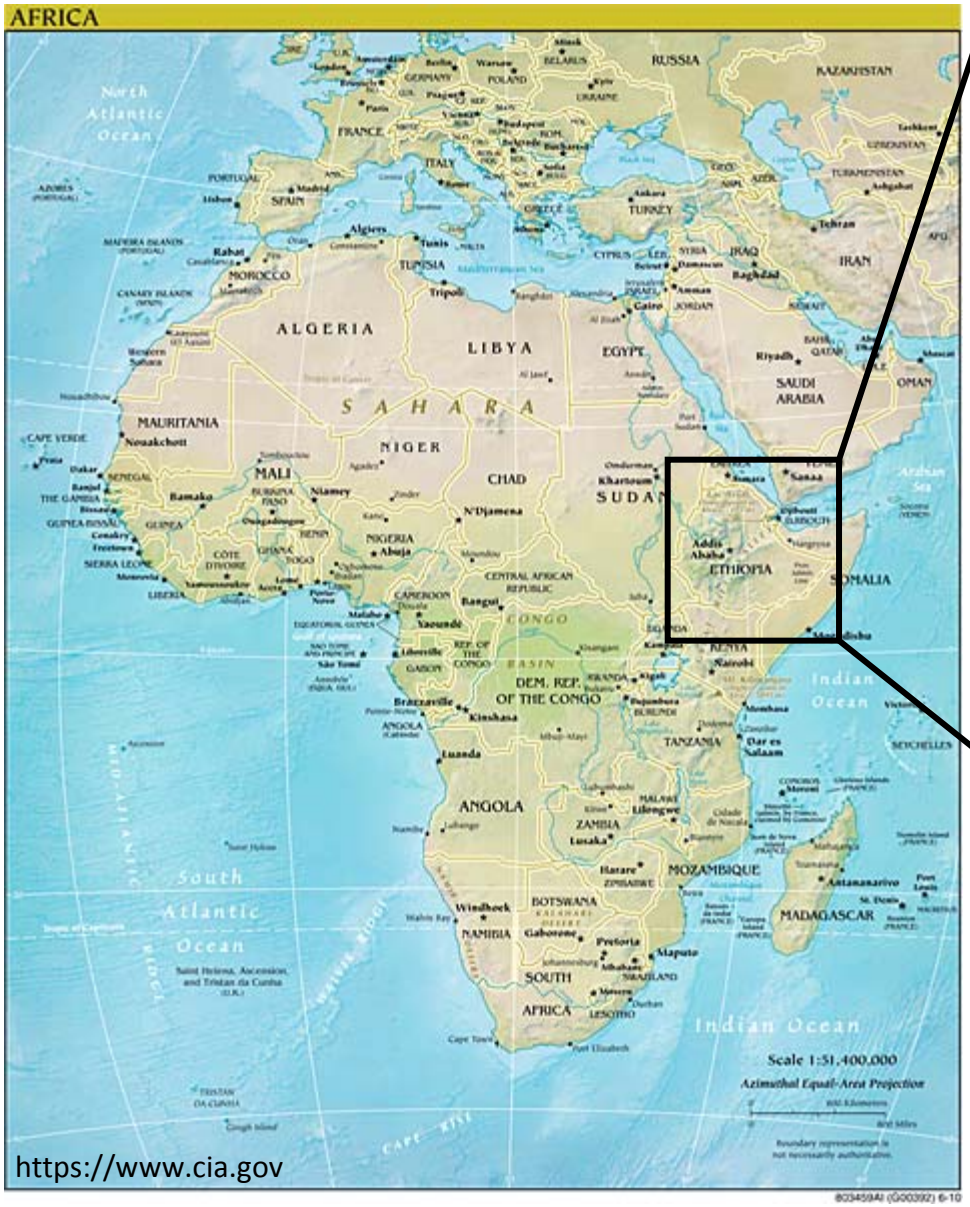


Designing Flexibility into Hydroelectric Projects: a case study of Ethiopia

Jonathan Baker

ESD.71

System Description



https://www.cia.gov

https://www.cia.gov

<u>Proposal to build 4 dams</u>

Hydroelectricity

Irrigation (2 dams only)

Prior Work: IMPEND

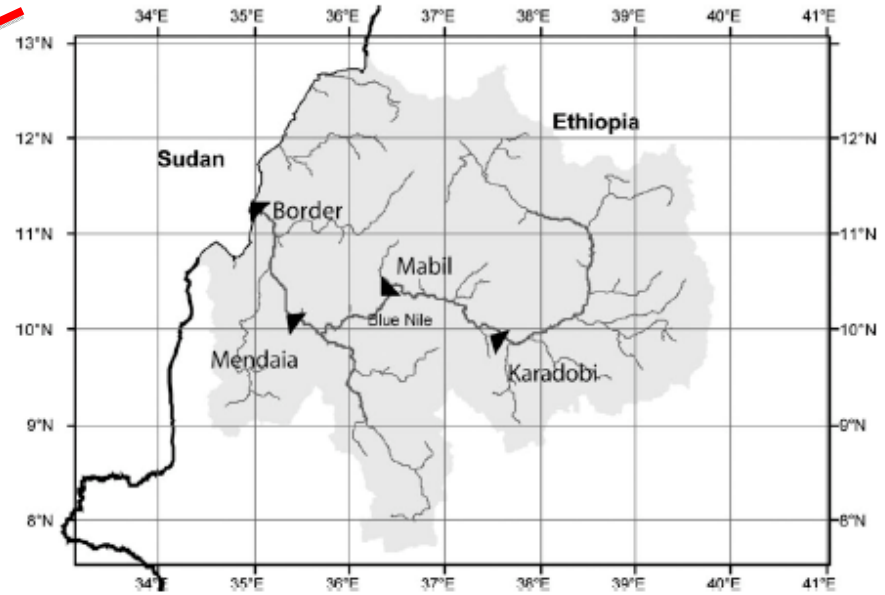


Fig. 2. Plan view of proposed hydroelectric dams along the Blue Nile, as proposed by the USBR

Block and Strzepek, 2010

IMPEND

- NPV of project (from Ag & Hydro)
- Transient Filling
- Stream-flow variability (seasonal and climatic)
- Construction Timing
- Constant price: Ag and Elec

What is the impact of considering a non-constant price for electricity?

Some Simplifications

- Did not use IMPEND for this work
  - Wanted to run MC
  - IMPEND computationally expensive

- Constructed a simplified NPV model
  - Neglected Agriculture: focus was on electricity
  - Simplified flow balance: ignored evaporation
  - Simplified transient filling stage model
  - Did not consider climate change
  - Neglected downstream flow policy

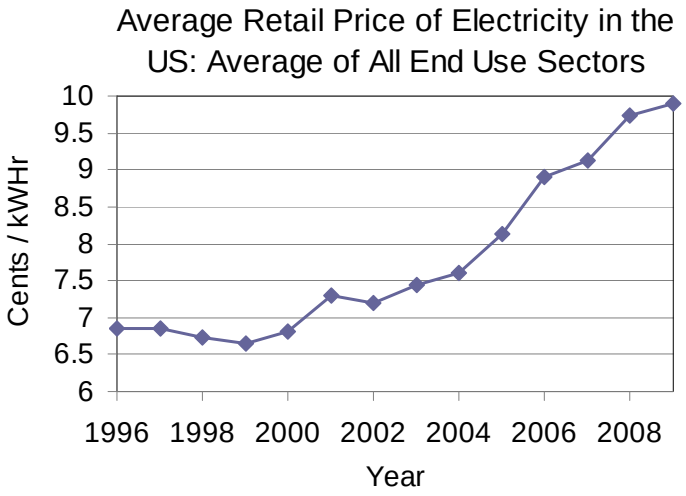
Design Levers

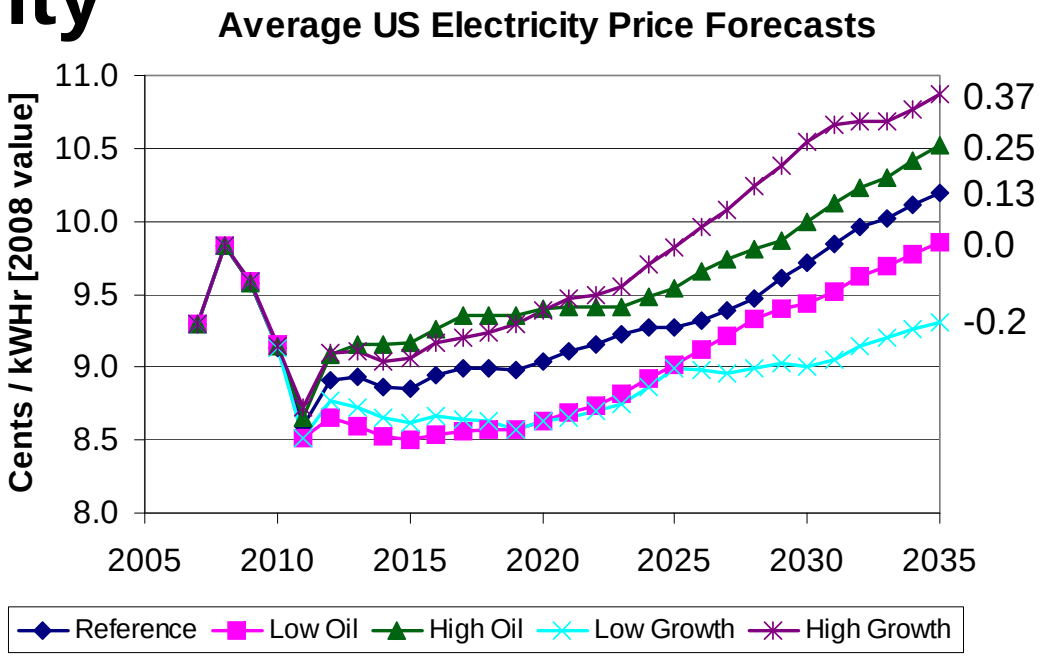
- Construction Options
  - When to build
  - Where to build (established by USBR study so not a consideration for this analysis)
  - Construction sequence

- Flow Policy?
  - Not necessarily under designers complete control
  - Will be influenced by international politics

Sources of Uncertainty

Electricity Price (US EIA)



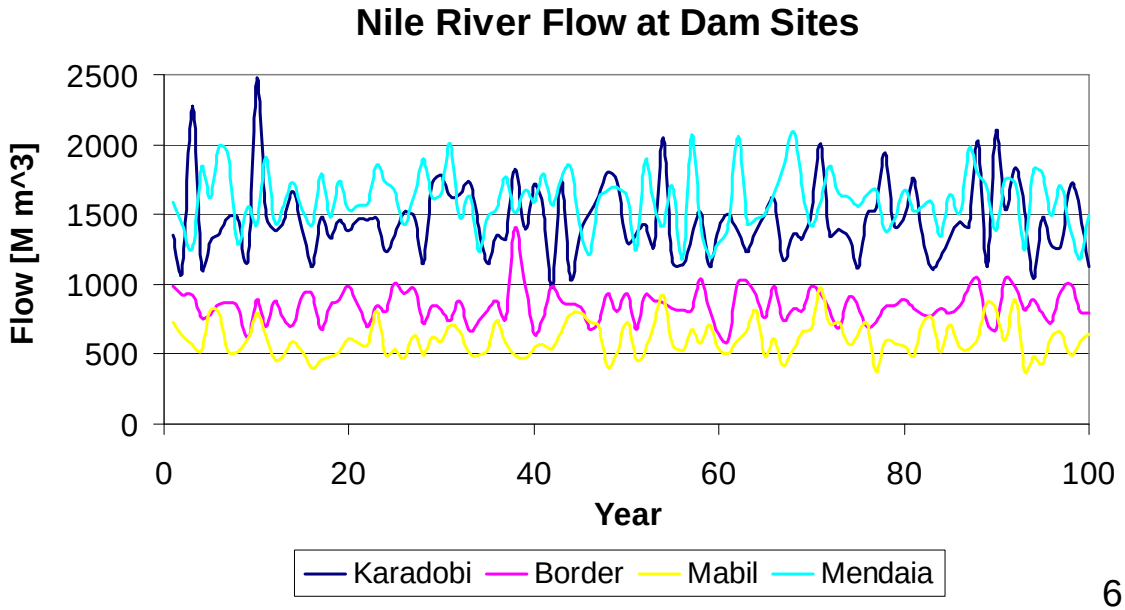


Stream Flow

Historical stream flow data from IMPEND / Paul Block

Stream flow – lognormal

Projected stream flow based on parameters from IMPEND stream flow data



Analysis Structure

Fixed System Design: Deterministic

- Build dams Karadobi, Border, Mabil, Mendaia in 7 year increments (adopted from IMPEND analysis)
- Analyzed for each electricity growth rate (no uncertainty)

Fixed System Design Under Uncertainty

- Construction sequence remains fixed
- Model volatility about the trend in electricity growth rate using GBM, 5 % volatility (MC of 1000 samples)

Flexible System Design Under Uncertainty

- Three alternative construction patterns (All At Once, Build two at a time)

Simplified NPV Model

- Costs (Block)
  - Fixed costs spread out over 7 years
  - Operational / Maintenance: fixed

Capital and operational / maintenance

Dam	Cap Cost [10^6]	O&M Cost [10^6]
Karadobi	2,213	15.9
Border	1,985	17.2
Mabil	1,792	13.5
Mendaia	2,114	17.9

Distribution of Capital costs during construction

Construction year	*1*	*2*	*3*	*4*	*5*	*6*	*7*
Portion of fixed cost [%]	10	15	20	20	20	10	5

- Benefits (Block / Strzepek)
  - Begin to accrue after reservoir has filled to 10 % capacity
  - Then assume dam can generate maximum capacity
  - 65 % efficiency

Benefits = η ·

Capacity (MW) ·

$Price_{Hydro}$ (¢/kWHr) ·

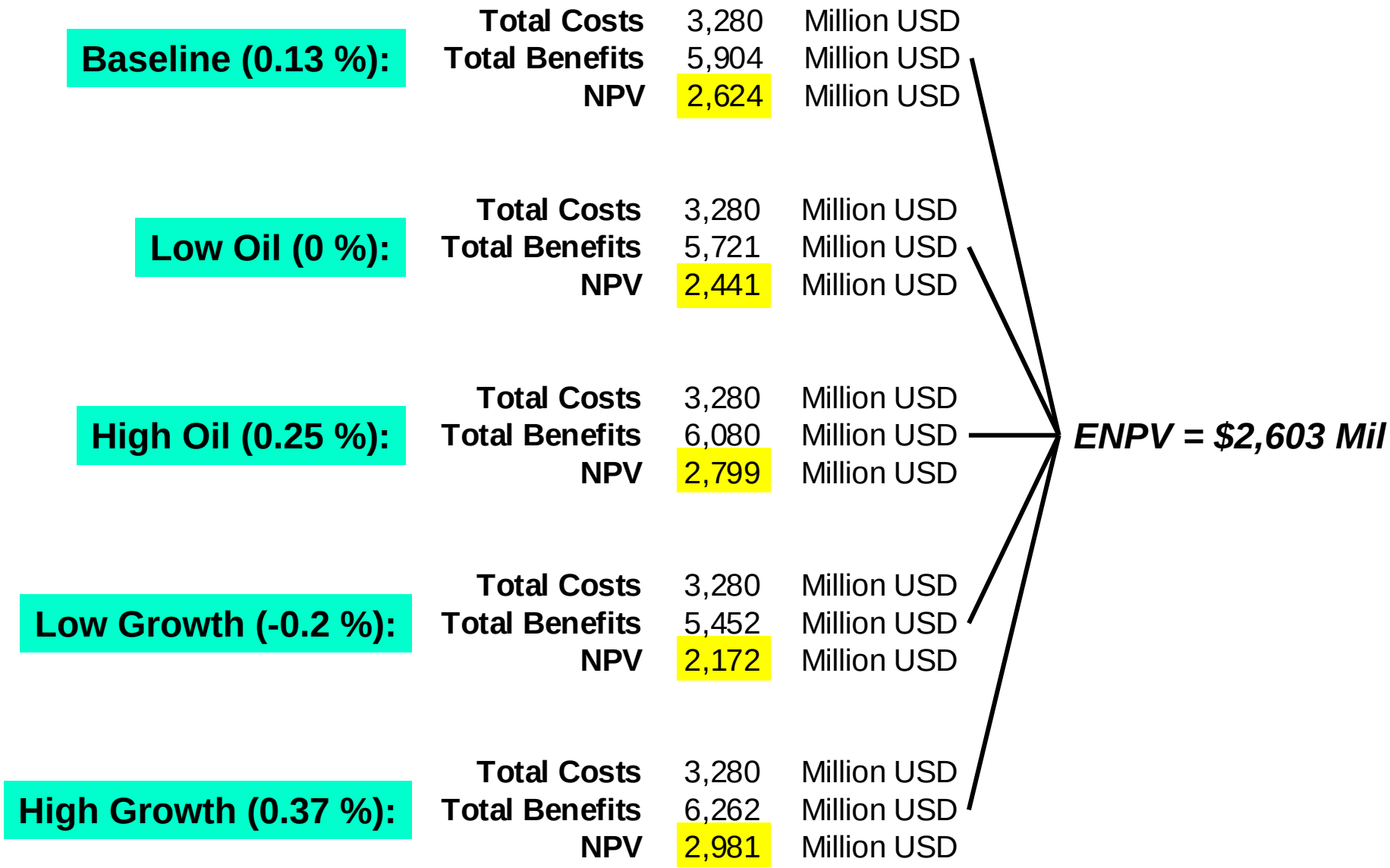
24 Hr · 365 Days / 1000

Yields benefits in $Million

Dam	Capacity [10^9 m^3]	Capacity [MW]
Karadobi	32.5	1350
Border	11.1	1400
Mabil	13.6	1200
Mendaia	15.9	1620

Discount Rate: 10 %

Fixed Design: Deterministic



Uncertainty and Flexibility

Baseline

Growth Rate 0.13%

	ENPV	CAPEX	RoI	P5	P95
No Flexibility	2,624	3,107	0.84	2,544	2,709
Flexibility: AAO	6,366	6,312	1.01	6,143	6,578
Flexibility: Ka, Bo	4,620	4,831	0.96	4,476	4,772
Flexibility: Me, Bo	5,283	4,793	1.10	5,130	5,435

Low Oil

Growth Rate 0.00%

	ENPV	CAPEX	RoI	P5	P95
No Flexibility	2,440	3,107	0.79	2,357	2,521
Flexibility: AAO	6,071	6,312	0.96	5,856	6,285
Flexibility: Ka, Bo	4,362	4,831	0.90	4,217	4,513
Flexibility: Me, Bo	5,023	4,793	1.05	4,858	5,180

High Oil

Growth Rate 0.25%

	ENPV	CAPEX	RoI	P5	P95
No Flexibility	2,798	3,107	0.90	2,710	2,883
Flexibility: AAO	6,656	6,312	1.05	6,432	6,881
Flexibility: Ka, Bo	4,874	4,831	1.01	4,710	5,025
Flexibility: Me, Bo	5,540	4,793	1.16	5,376	5,704

Low Growth

Growth Rate -0.20%

	ENPV	CAPEX	RoI	P5	P95
No Flexibility	2,173	3,107	0.70	2,091	2,255
Flexibility: AAO	5,609	6,312	0.89	5,415	5,816
Flexibility: Ka, Bo	3,975	4,831	0.82	3,836	4,126
Flexibility: Me, Bo	4,632	4,793	0.97	4,481	4,790

High Growth

Growth Rate 0.37%

	ENPV	CAPEX	RoI	P5	P95
No Flexibility	2,979	3,107	0.96	2,890	3,068
Flexibility: AAO	6,955	6,312	1.10	6,723	7,185
Flexibility: Ka, Bo	5,121	4,831	1.06	4,959	5,279
Flexibility: Me, Bo	5,804	4,793	1.21	5,651	5,968

***ENPV*, *P5*, *P95*:** AAO

***CAPEX*:** No Flex

***RoI*:** Me, Bo

Reflections

- Greatest Use for Flexibility
  - *ENPV/P5/P95*: value of flexible option increases with the growth rate
  - *RoI & CAPEX*: flexibility equally valuable

- Lessons Learned
  - Flexibility is only as valuable as your decision rule is sensible; simply changing the design does not automatically improve the design performance
  - The “best” design will depend on what criteria is important to the analyst
  - Price of hydropower does not appear to have significant impacts on assessment criteria

Acknowledgments

I am indebted to the help and guidance of Prof. Ken Strzepek, soon to be Prof. Michel Cardin, and Prof. Richard de Neufville

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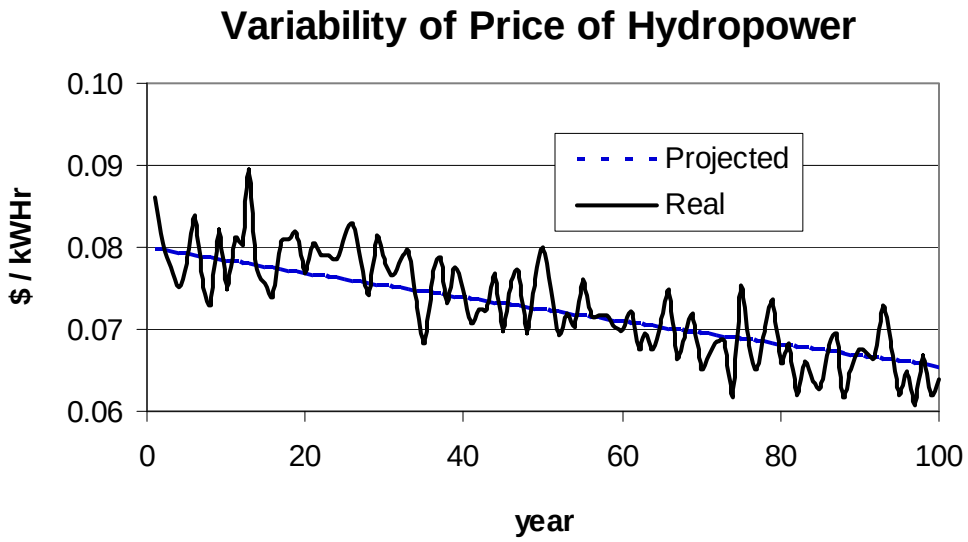
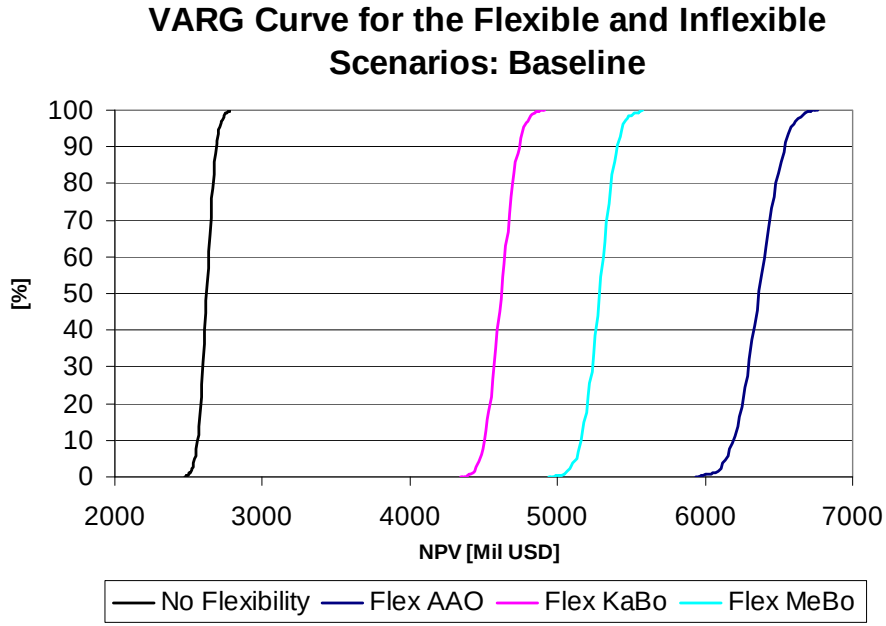
Annual Energy Outlook (AEO). 2010. Table 8, Electricity Supply, Disposition, Prices, and Emissions, EIA AEO, accessed November 27, 2010 at: <http://eia.gov/oiaf/aeo/index.html>

Block, P., K. Strzepek, and B. Rajagopalan, 2007: Integrated management of the Blue Nile Basin in Ethiopia : Hydropower and irrigation modeling, *IFPRI Discussion Paper 700*, International Food Policy Research Institute (IFPRI): Washington, D.C., 25 pages

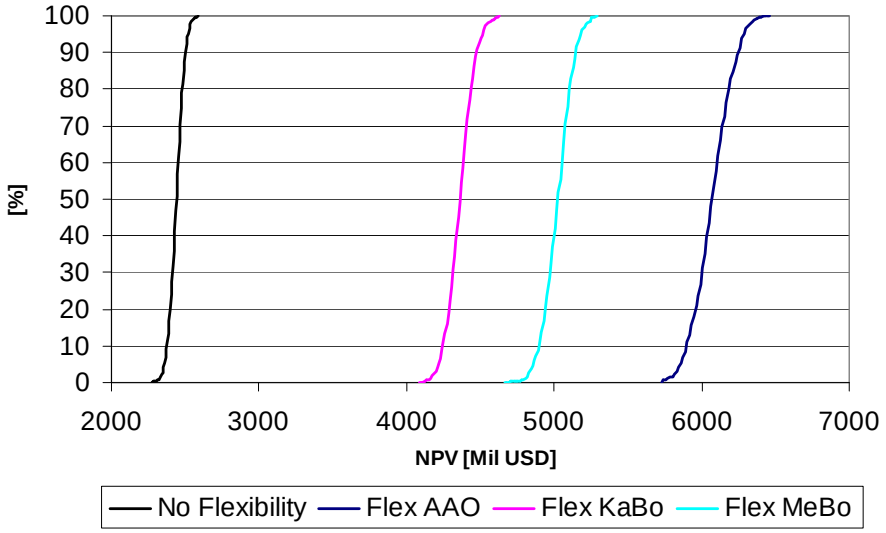
Block, P. and Strzepek, K. 2010. Economic Analysis of Large-Scale Upstream River Basin Development on the Blue Nile in Ethiopia Considering Transient Conditions, Climate Variability and Climate Change, *Journal of Water Resources Planning and Management*, Vol. 136, No. 2, doi:10.1061/(ASCE)WR.1943-5452.0000022

EIA. Average Retail Price of Electricity to Ultimate Customers: Total by End-Use Sector, accessed November 27, 2010 at: <http://www.eia.doe.gov/cneaf/electricity/epm/table5_3.html>

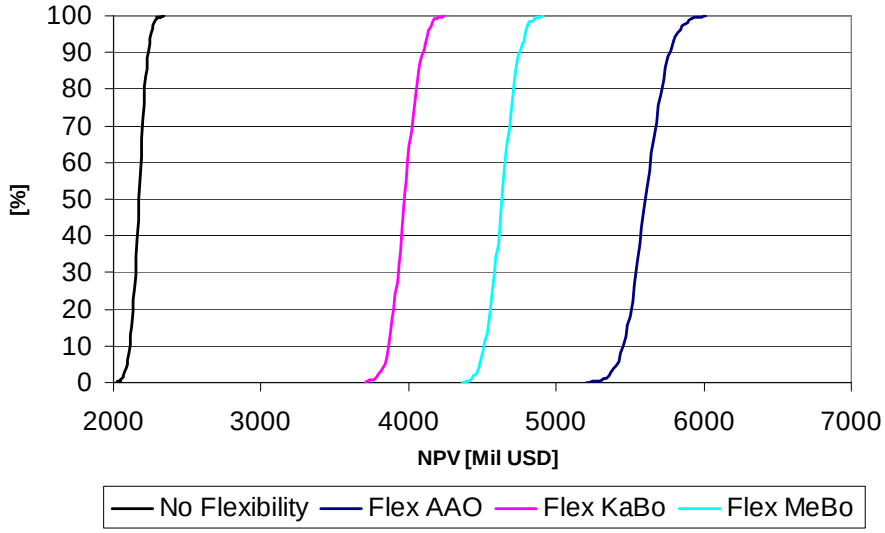

Variability of Price of Hydropower
0.10
0.09
0.08
0.07
0.06
$ / kWHr
Projected
Real
0
20
40
60
80
100
year


VARG Curve for the Flexible and Inflexible Scenarios: Baseline
100
90
80
70
60
50
40
30
20
10
0
[%]
2000
3000
4000
5000
6000
7000
NPV [Mil USD]
No Flexibility
Flex AAO
Flex KaBo
Flex MeBo

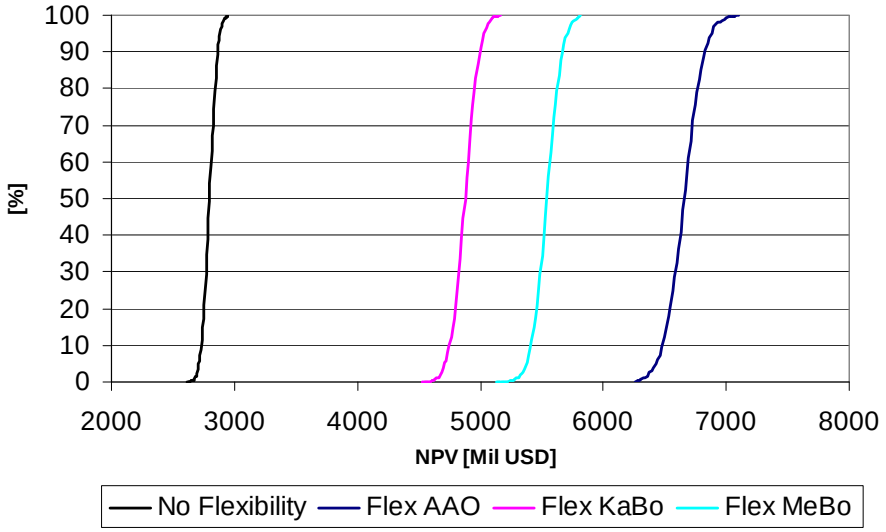
VARG Curve for the Flexible and Inflexible Scenarios: Low Oil



VARG Curve for the Flexible and Inflexible Scenarios: Low Growth



VARG Curve for the Flexible and Inflexible Scenarios: High Oil



VARG Curve for the Flexible and Inflexible Scenarios: High Growth