Overview

- Modeling Electric Power Expansion
- A Case Study from Turkey

Stochastic Optimization

- Electric Power Expansion - standard

The Traditional Case

$$\text{Minimize} \quad \text{total} \quad \text{cost} = \sum_{j=1}^{J}\sum_{v=1}^{T} fc_{jv}X_{jv} + \sum_{j=1}^{J}\sum_{t=1}^{T}\sum_{v=0}^{t}\sum_{s=1}^{S} vc_{jtv}L_{jtvs}\theta_s$$

Subject to

$$\sum_{j=1}^{J}\sum_{v=0}^{t} a_{jv}X_{jv} \geq D_{ts}(1+m) \qquad s=1, \quad t=1,\ldots,T$$

$$\sum_{j=1}^{J}\sum_{v=0}^{t} L_{jtvs} \geq D_{ts} \qquad s=1,\ldots.,S \quad t=1,\ldots,T$$

$$L_{jtvs} \leq a_{jv}X_{jv}$$

Technological + Regulatory Constraints

Stochastic Optimization

- Electric Power Expansion - stochastic

$$E_t(NPV) = \sum_{j=1}^{J}\sum_{\tau=t}^{T}\sum_{v=0}^{\tau}\sum_{s=1}^{S} E_{z_\tau}\left(P_\tau\right)\cdot L_{j\tau vs}\cdot\theta_s$$

$$-\sum_{j=1}^{J}\sum_{v=1}^{T} fc_{jv}\cdot X_{jv} - \sum_{j=1}^{J}\sum_{\tau=t}^{T}\sum_{v=0}^{\tau}\sum_{s=1}^{S} E_{z_\tau}\left(vc_{j\tau v}\right)\cdot L_{j\tau vs}\cdot\theta_s$$

S. to

$$\sum_{j=1}^{J}\sum_{v=0}^{\tau} L_{j\tau vs} \geq E_{z_\tau}\left(D_{\tau s}\right) \qquad s = 1,\ldots.,S \qquad \tau = 1,\ldots,T$$

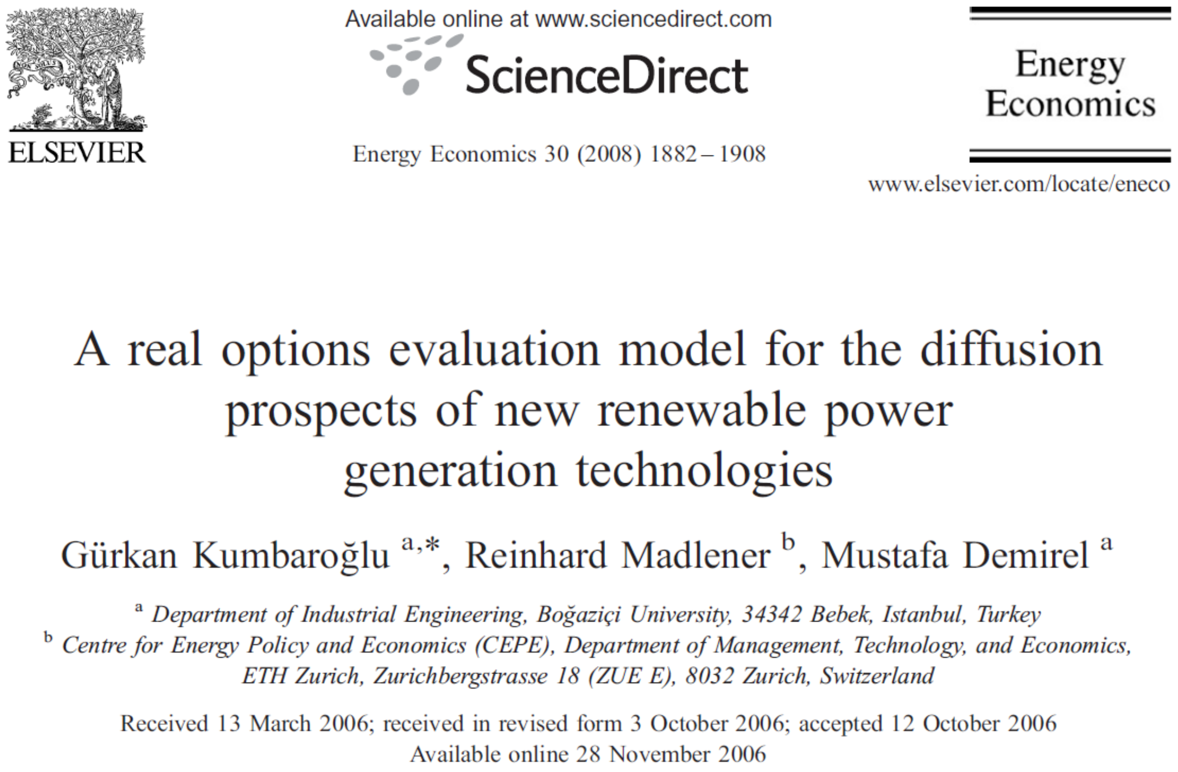
$$vc_{j,\tau} = \alpha_0 + \sum_{i=1}^{p}\alpha_i vc_{\tau-i} + \sum_{i=0}^{q}\beta_i\varepsilon_{\tau-i}$$

$$\sum_{j=1}^{J}\sum_{v=0}^{\tau} a_{jv}X_{jv} \geq E_{z_\tau}\left(D_{\tau s}\right)\cdot(1+m) \qquad s=1,\ \tau=1,\ldots,T$$

$$L_{j\tau vs} \leq a_{jv}X_{jv} \qquad , \qquad \sum_{s=1}^{S} L_{j\tau vs}\theta_s \leq b_j X_{jv}$$

& other constraints

Real Options Approach to Energy Investments



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Energy Economics 30 (2008) 1882–1908

Energy
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A real options evaluation model for the diffusion prospects of new renewable power generation technologies

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Received 13 March 2006; received in revised form 3 October 2006; accepted 12 October 2006
Available online 28 November 2006

Outline

- Introduction
- Theoretical Background
  - The Real Options Approach
  - Learning Curves and RET Adoption
- Model Description
- Empirical Analysis
  - The Turkish Electricity Supply Industry
  - Model Calibration
  - Results
- Conclusions

Introduction

- Turkey on the way to EU membership
  - Recently ratified the UNFCCC, Kyoto in line
  - Great renewable energy potentials
- Uncertain prospects for the diffusion of RETs
  - High investment costs of RETs
  - Uncertainty due to electricity market restructuring
- Technology Adoption Modeling
  - Challenges on traditional investment planning OR models
  - Real Options approach to deal with uncertainty
  - Learning Curve theory to reflect RET cost reductions

Theoretical Background

- The Real Options Approach
  - *Dixit/Pindyck, 1994*
  - Resolution of uncertainty over time, dynamic programming
  - *Crystal Ball*® software *(Mun, 2002)*
  - Variety of applications to energy industry issues

    e.g. *Ronn (2003), Frayer/Uludere (2001), Keppo/Lu (2003)*

- Learning Curves and RET Adoption
  - Reduction in cost as a function of cumulative production
  - Progress ratios, learning rates
  - Global progress ratios *(Junginger et al., 2005)*
  - Many empirical studies on learning curves in energy research

    e.g. *Ibenholt 2002, Junginger et al. 2005, Kamp et al. 2004, Neij 1997/1999*

Model Description

- Maximizing the Net Present Value (*NPV*)

$$NPV_t(X_{i,v=t}) = \max \left\{ \begin{array}{l} \sum_i \sum_{z=t+lt(i)}^{t+lt(i)+el(i)} p_z (1+r)^{-(z-t)} L_{i,z,v=t}\ \theta_{i,z,v=t} \\ -\left\{ \forall \sum_i L_{i,z,v}\theta_{i,z,v} \geq d_z \mid \sum_i \sum_{z=t+lt(i)}^{t+lt(i)+el(i)} p_z (1+r)^{-(z-t)} \left\{ L_{i,z,v=t}\theta_{i,z,v=t} - d_z \right\} \right\} \\ -\sum_i \sum_{z=t+lt(i)}^{t+lt(i)+el(i)} vc_{i,z,v=t} (1+r)^{-(z-t)} L_{i,z,v=t}\ \theta_{i,z,v=t} \\ -\sum_i fc_{i,v=t} X_{i,v=t} \\ +\frac{1}{1+r} E_t\left(NPV_{t+1}(X_{i,v=t+1}) \right) \end{array} \right.$$

Variables/parameters:
p ... el. price
r ... real interest rate
L ... load
θ ... duration hours

d ... peak power demand
vc ... var. cost
fc ... fixed cost
lt ... construction lead time
el ... economic lifetime

Indices:
i ... plant type
z ... year
v ... vintage
t ... time

Model Description

- Meeting peak load demand

$$\sum_i \sum_{v=z-lt(i)-el(i)}^{z-lt(i)} L_{i,z,v}\theta_{i,z,v} \geq d_z(1+m)$$

$$\forall \quad t + lt(i) + el(i) \geq z \geq t$$

✓ price-elastic demand for electricity (elasticity increases with degree of market opening)

$$d_z(p_z) = \alpha\, p_z^{\varepsilon_z}$$

Model Description

- Considering capacity availability

$$L_{i,z,v} \leq a_i X_{i,v}$$

$$L_{i,z,v} \frac{\theta_{i,z,v}}{8760} \leq cf_i X_{i,v}$$

$$\forall\ t + lt(i)+el(i) \geq z \geq t + lt(i)\ ,\ \ v \leq t$$

Model Description

- Introducing uncertainty

$$\delta p_z = p_{z-1}\left(\mu\,\delta z + \sigma\;\varepsilon\sqrt{\delta z}\right)$$

$$\delta vc_{i,z,v} = vc_{i,z-1,v}\left(\mu\,\delta z + \sigma\;\varepsilon\sqrt{\delta z}\right)$$

Model Description

- Integrating technological learning

$$fc_{i,v} = fc_{i,v=2000}\, CC^{-li}$$

$$PR=2^{-li}$$

Empirical Analysis

- The Turkish Electricity Supply Industry

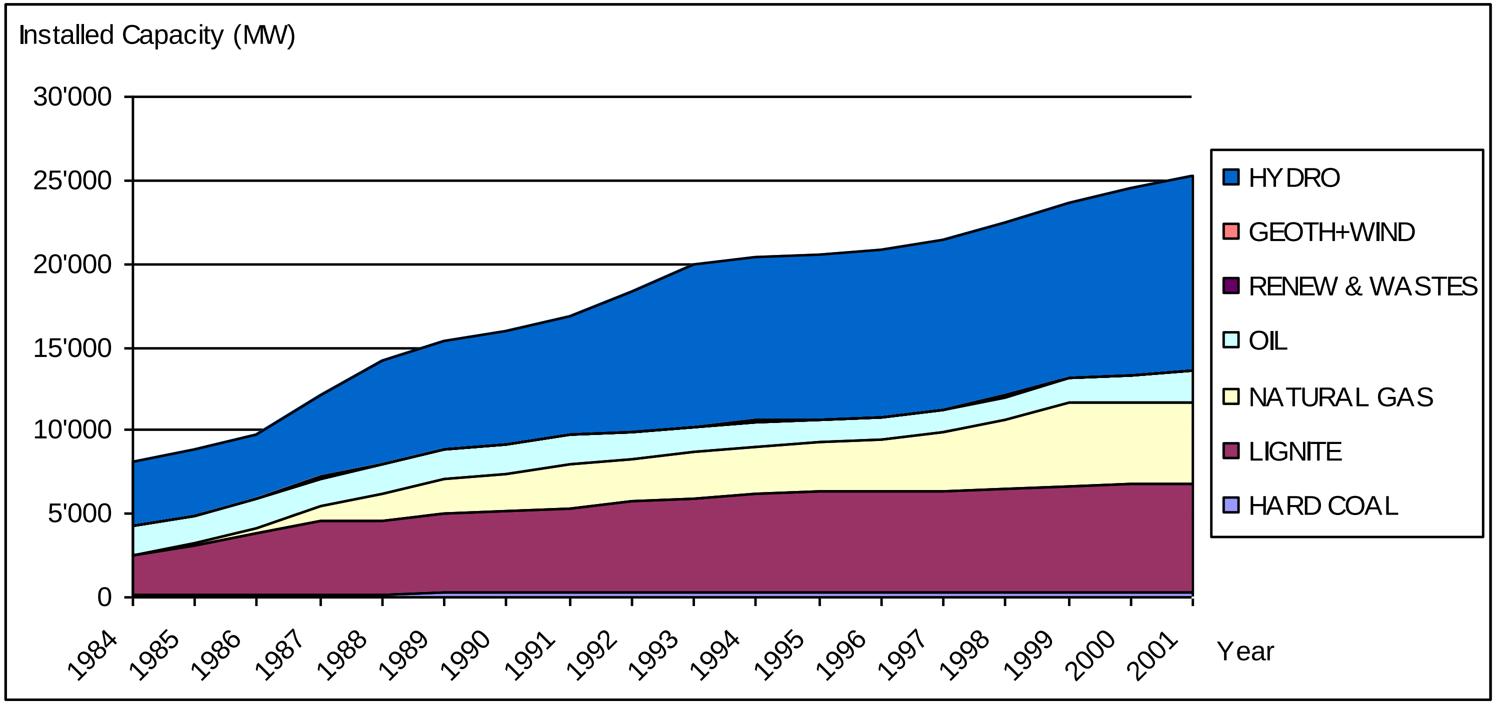


Figure 1. Development of electricity generating capacity in Turkey, 1984-2001 (Source: TEIAS, 2002)

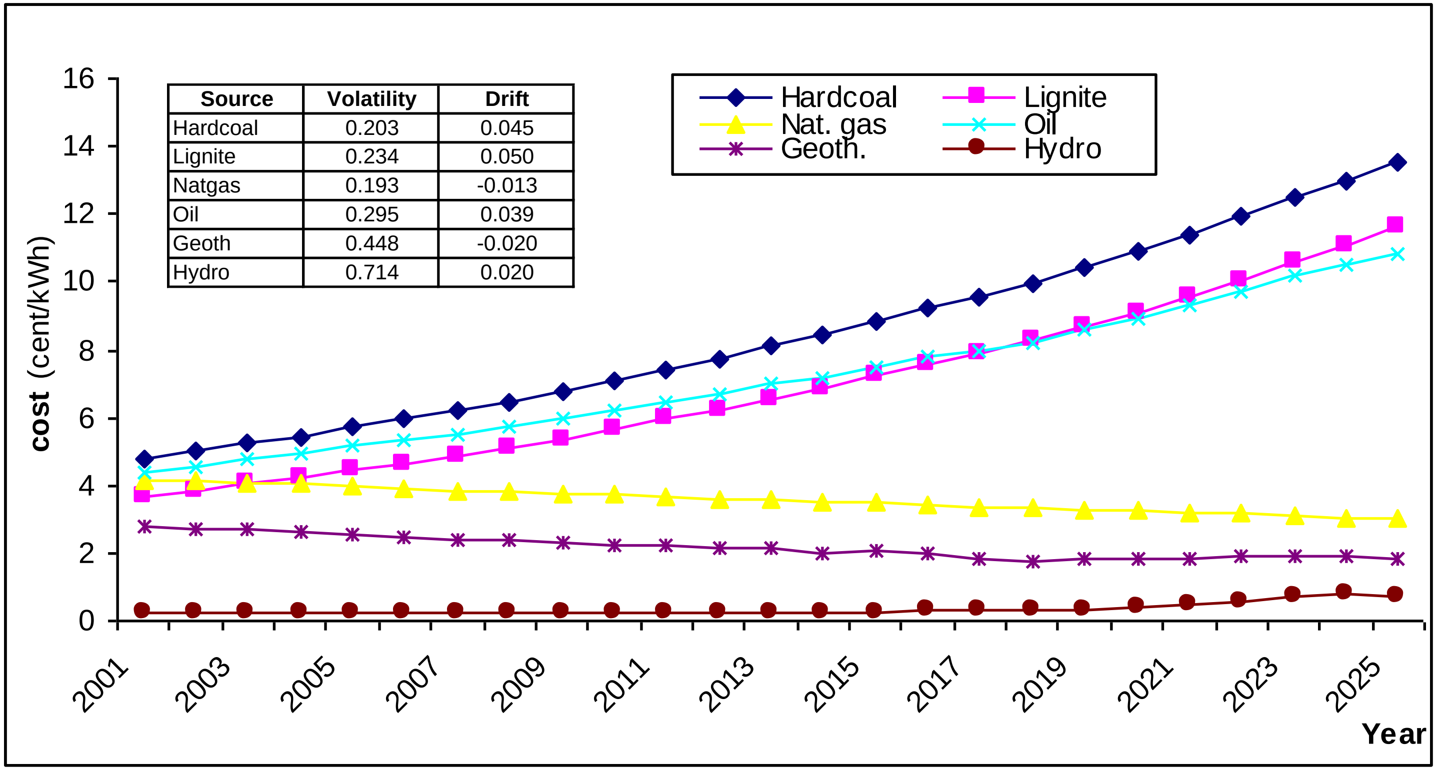
Table 1. Renewable electricity potentials and current and expected RET installations in Turkey

Energy source	***Theoretical potential***	***Technical potential***	***Economic potential***	***Current (2001) installation***	***Expected contribution / Policy goals***		
					2005	***2010***	***2020***
Hydro power	49 GW 430 TWh	216 TWh	35 GW 125 TWh	11.6 GW 24 TWh	14.8 GW 48 TWh	65 - 85 TWh Goal: 100% of potential	29 - 35 GW 98 - 110 TWh
Wind power	88 GW > 400 TWh	83 GW- 124 - 166 TWh	10 - 20 GW	18.9 MW 62.4 TWh	643 MW	0.6 - 4 GW	1 GW
Geothermal power	4.5 GW_e tot.	2.0 GW_e		17.5 MW 89.6 GWh	0.04 - 0.15 GW_e 22 TWh	0.3 - 0.5 GW_e 44 TWh	1 GW_e 96 TWh
Solar	102 TWh proven		102 TWh	1.5 TWh		Goal: 40 MW_e (PV)	9 TWh
Biogas	12 - 23 TWh			5.4 MW_e	10 MW_e (Biogas-Waste)		
Biomass	197 - 372 TWh			91 MW		86 TWh	87 TWh
Total RET				**104 TWh**		**25 GW**	**30 GW**

Data sources: see paper

Empirical Analysis

- Model Calibration



Source	Volatility	Drift
Hardcoal	0.203	0.045
Lignite	0.234	0.050
Natgas	0.193	-0.013
Oil	0.295	0.039
Geoth	0.448	-0.020
Hydro	0.714	0.020

Figure 2. Variable cost projections for existing power generation technologies, 2001-2025

Empirical Analysis

- Model Calibration

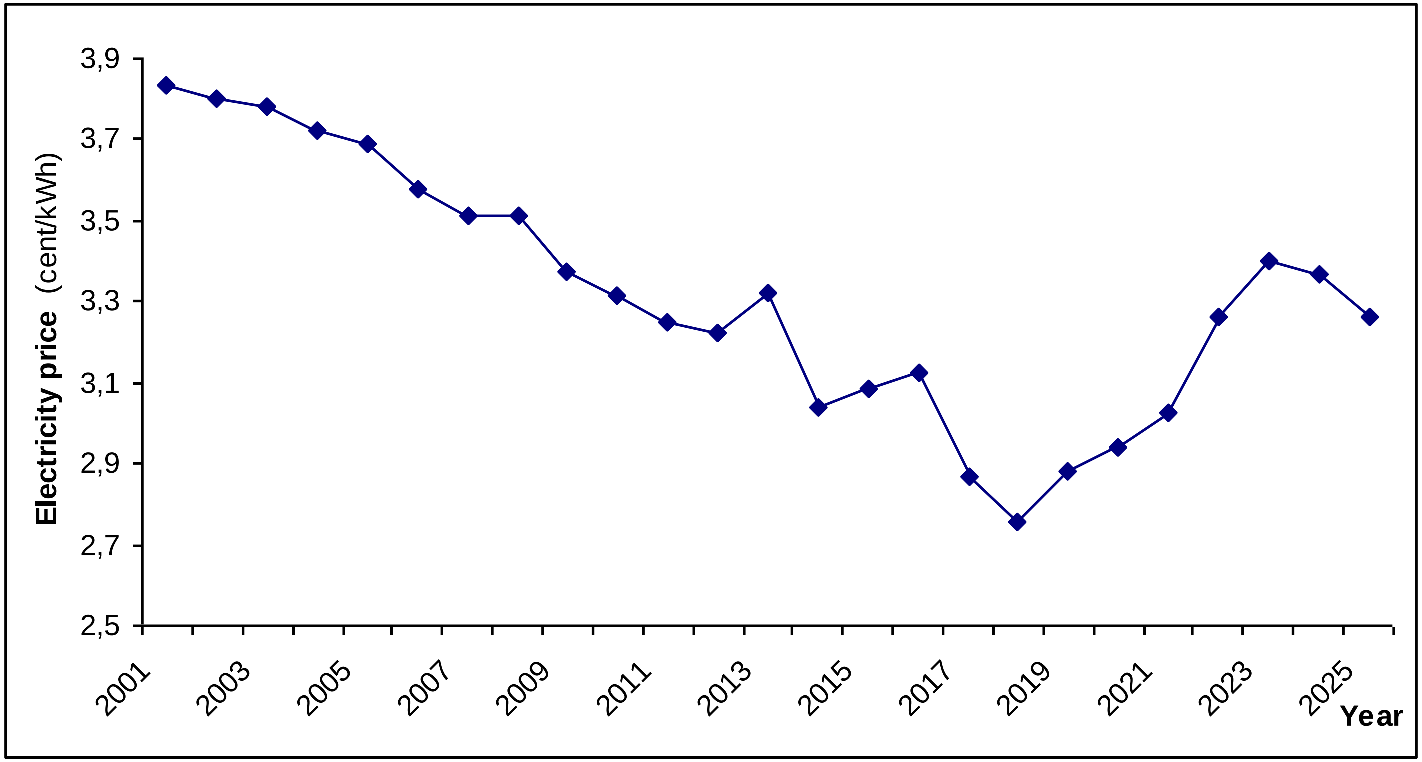


Figure 3. Electricity price projections, 2001-2025

Real Options Approach to Energy Investments

Table 3. Candidate power generation technologies: costs, assumed availability, learning rates and construction lead times

Technology	**Inv. cost** *($/kW)*	**Annual fixed O&M cost** *($/kW)*	**Availability factor**	**Capacity factor**	**Learning rate**	**Construction lead time** *(years)*
Conventional						
Coal FBC CHP plant	3600	144	0.80	0.70	0.05	4
Pulverised coal power plant	1488	44.4	0.75	0.80	0.05	4
Integrated coal gasif. power plant	1260	64.8	0.75	0.80	0.05	4
Oil fired power plant	1032	28.8	0.75	0.80	0.01	3
Natural gas CC power plant	972	25.2	0.75	0.65	0.01	3
Gas turbine CHP plant	912	13.2	0.80	0.60	0.01	3
Lignite fired power plant	1728	44.4	0.75	0.75	0.01	4
Integrated lignite gasif. power plant	1920	37.2	0.75	0.45	0.05	4
Nuclear LWR power plant	2928	64.2	0.75	0.95	0.01	6
Renewable						
Biomass gasifier dedic. STAG (NH)	2448	240	0.75	0.80	0.15	3
Biomass gasifier SOFC*	3120	312	1.00	0.80	0.15	3
Biomass gas turbine CHP	2040	51	0.80	0.80	0.15	3
Solar PV	6000	24.6	0.90	0.15	0.20	2
Large onshore wind turbine	1140	21.6	0.90	0.25	0.1	1
Large onshore wind turbine storage	1632	26.4	0.90	0.25	0.1	1
Large offshore wind turbine storage	2340	37.2	0.90	0.25	0.08	2
Low head hydro	3420	30	0.80	0.47		10
Medium and high head hydro	2280	22.8	0.85	0.34		10
Hydro pumped storage	3420	45.6	0.92	0.40		10
Geothermal power plant	1236	31.2	0.70	0.90		2

Empirical Analysis

- Model Calibration

Table 4. Scenario assumptions

Scenario	**Upper bound on capacity addition per technology**	**Price elasticity (2020 → 2025)**	**Technology adoption restrictions**
FLEX	2 GW p.a.	-0.01 → -0.05	No restriction
NF1	1 GW p.a.	-0.01 → -0.02	No restriction
NF2	1 GW p.a.	-0.01 → -0.02	Natgas/Total Cap. ≤ 40%
NF3	1 GW p.a.	-0.01 → -0.02	Wind Turbine Licensing
NF4	1 GW p.a.	-0.01 → -0.02	Draft Law (8% Renew.)

Empirical Analysis

- Results

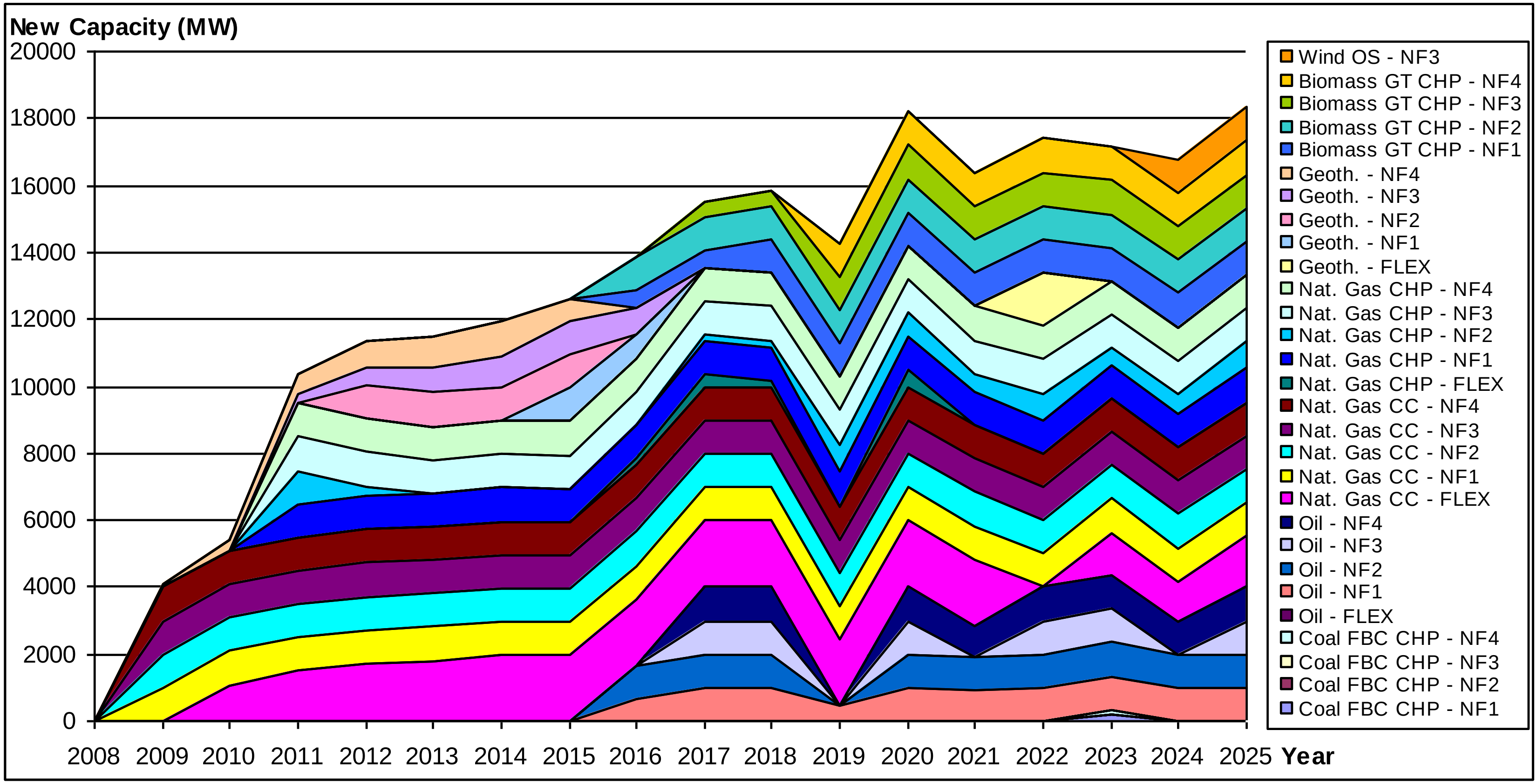


Figure 4. Composition of annual capacity additions, 2008-2025

Empirical Analysis

- Results

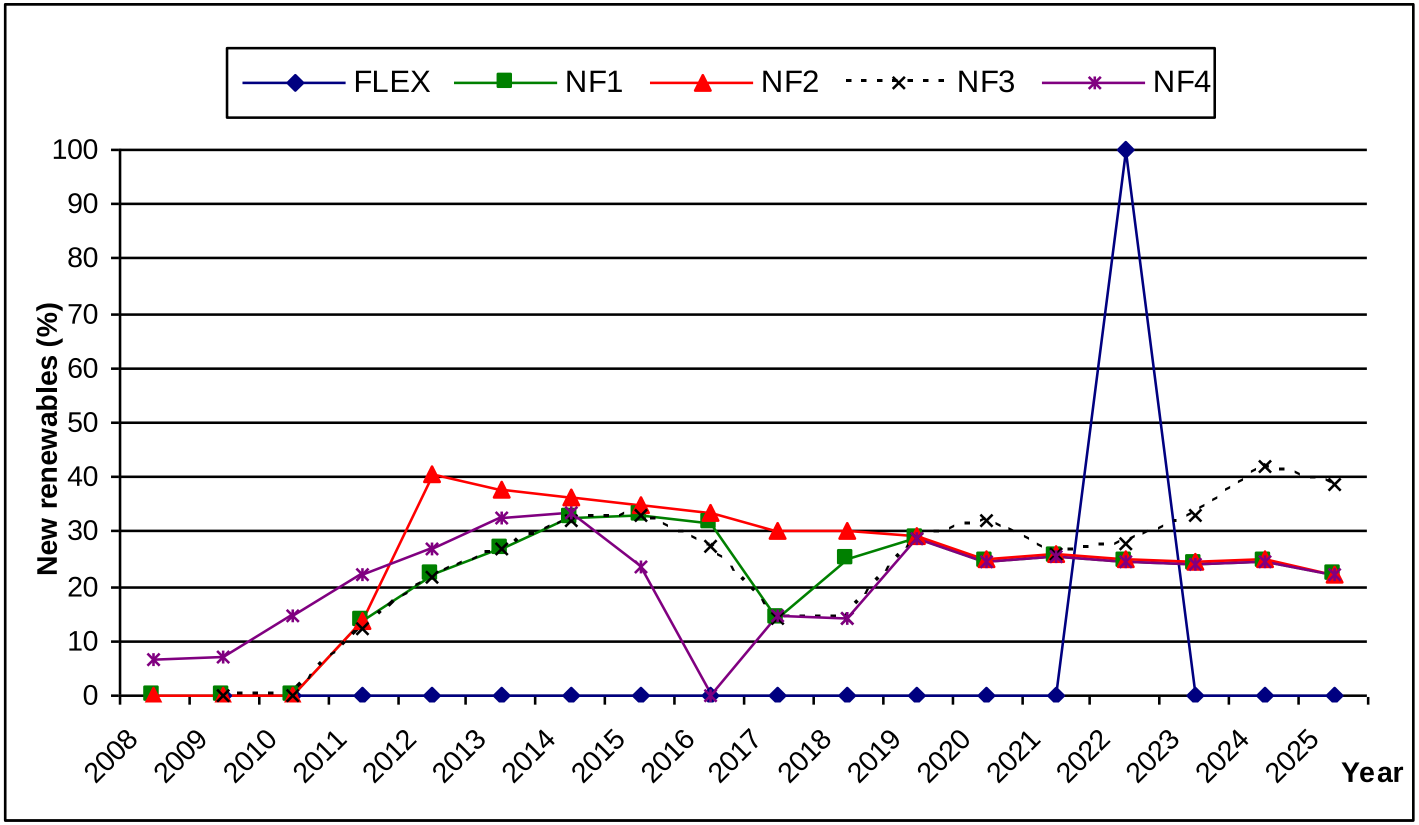


Figure 5. Percentage share of renewables among new capacity additions, 2008-2025

Conclusions

- ➢ RO dynamic programming formulation & learning curve integration for power generation investment planning

- ➢ The Case of Turkey

  - ✓ Diffusion of renewable energy technologies other than geothermal occurs only if targeted policies/promotion exists

  - ✓ Long lead times discourage hydropower investments under uncertainty

  - ✓ Natural gas CC remains the most attractive option

  - ✓ Draft renewable energy law under discussion induces technological learning and can significantly affect the evolution of the technological structure in the power sector

  - ✓ Opportunities for technological learning via Kyoto flexibility mechanisms