Modeling Technological Change in Energy Production and Use

National Academy of Science

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U.S. Energy Information Administration
Independent Statistics and Analysis

Overview

- Key concepts in technological change
  - how economists define technological change
  - technology supply and demand
  - the innovation system
- Representing technological change in energy-economic models
  - examples from EIA's National Energy Modeling System (NEMS)
- Key drivers of technological change in energy modeling
  - examples from EIA-NEMS analysis
- Summary of modeling challenges

Key concepts in the process of technological change

How do economists define technological change?

- Technological change is the process by which the economy changes over time, in terms of the products produced and the processes used for production, so that a technological advance...
  - enables the production of greater or higher-quality outputs from a given amount of inputs as time proceeds
- Energy is an essential input into
  - intermediate production of goods and services
  - final consumption of household services (e.g., lighting, heating, personal mobility)
- Energy produces both desirable and undesirable outputs (e.g., pollution)

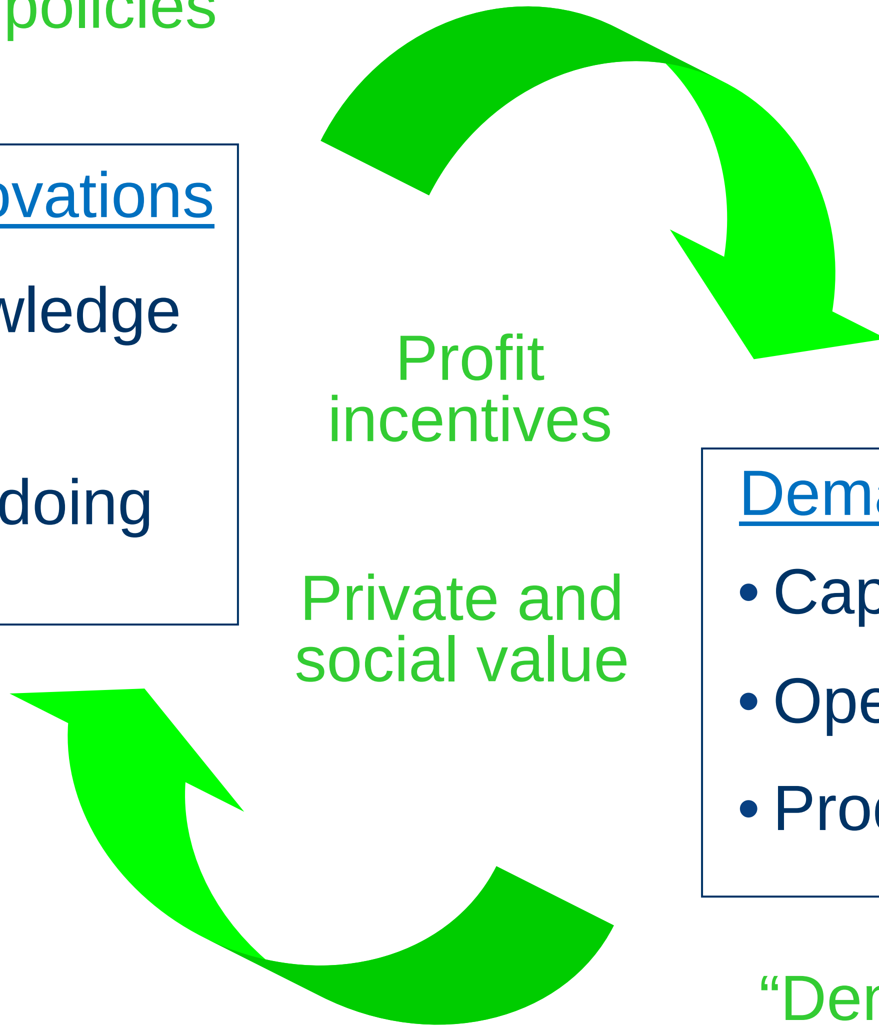
Technology supply and demand

"Supply-push" policies

↓

Supply of innovations

- State of knowledge
- RD&D
- Learning-by-doing



Demand for technology

- Capital cost
- Operating cost
- Product qualities

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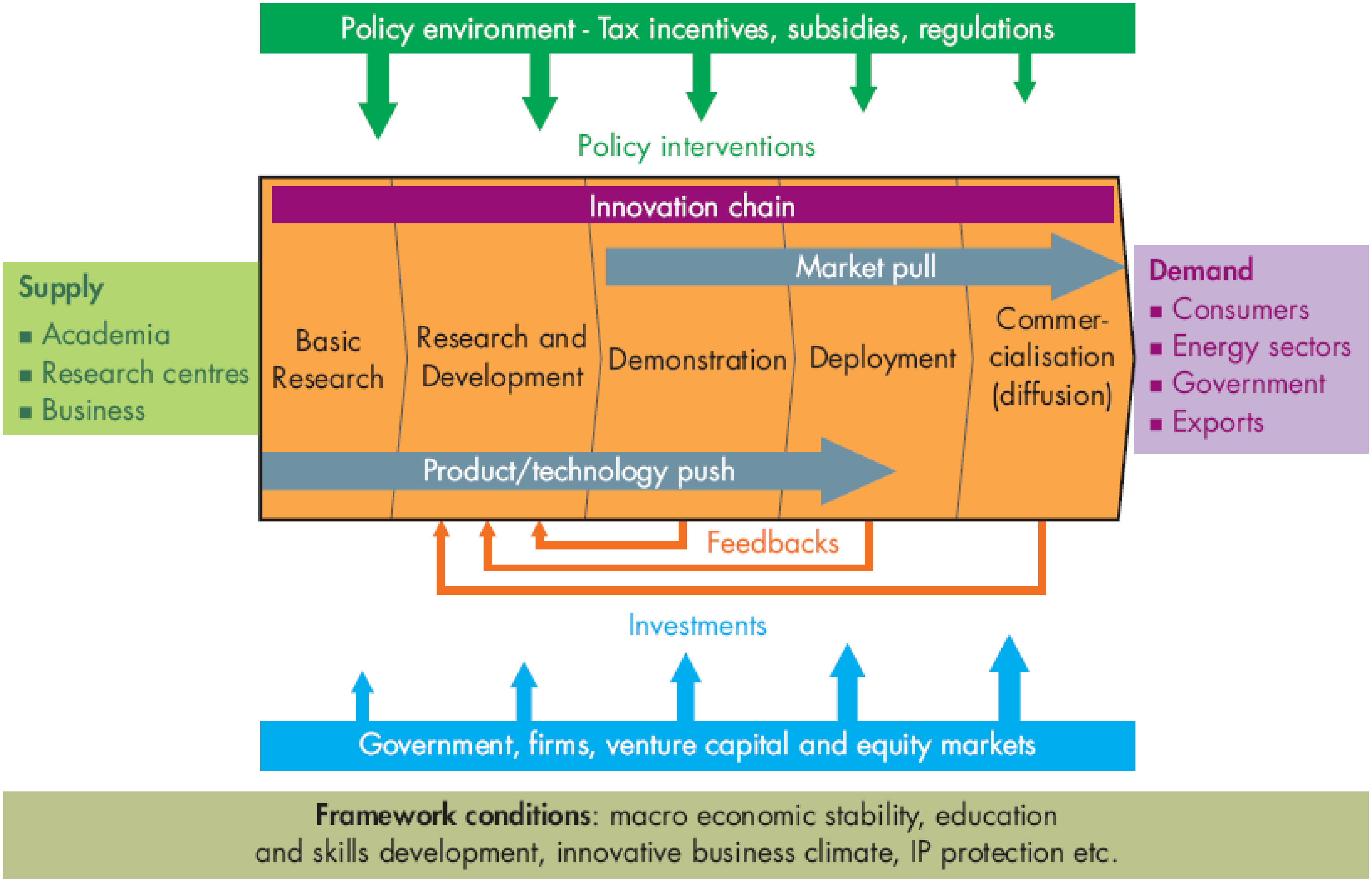
"Demand-pull" policies

Schematic of the innovation system



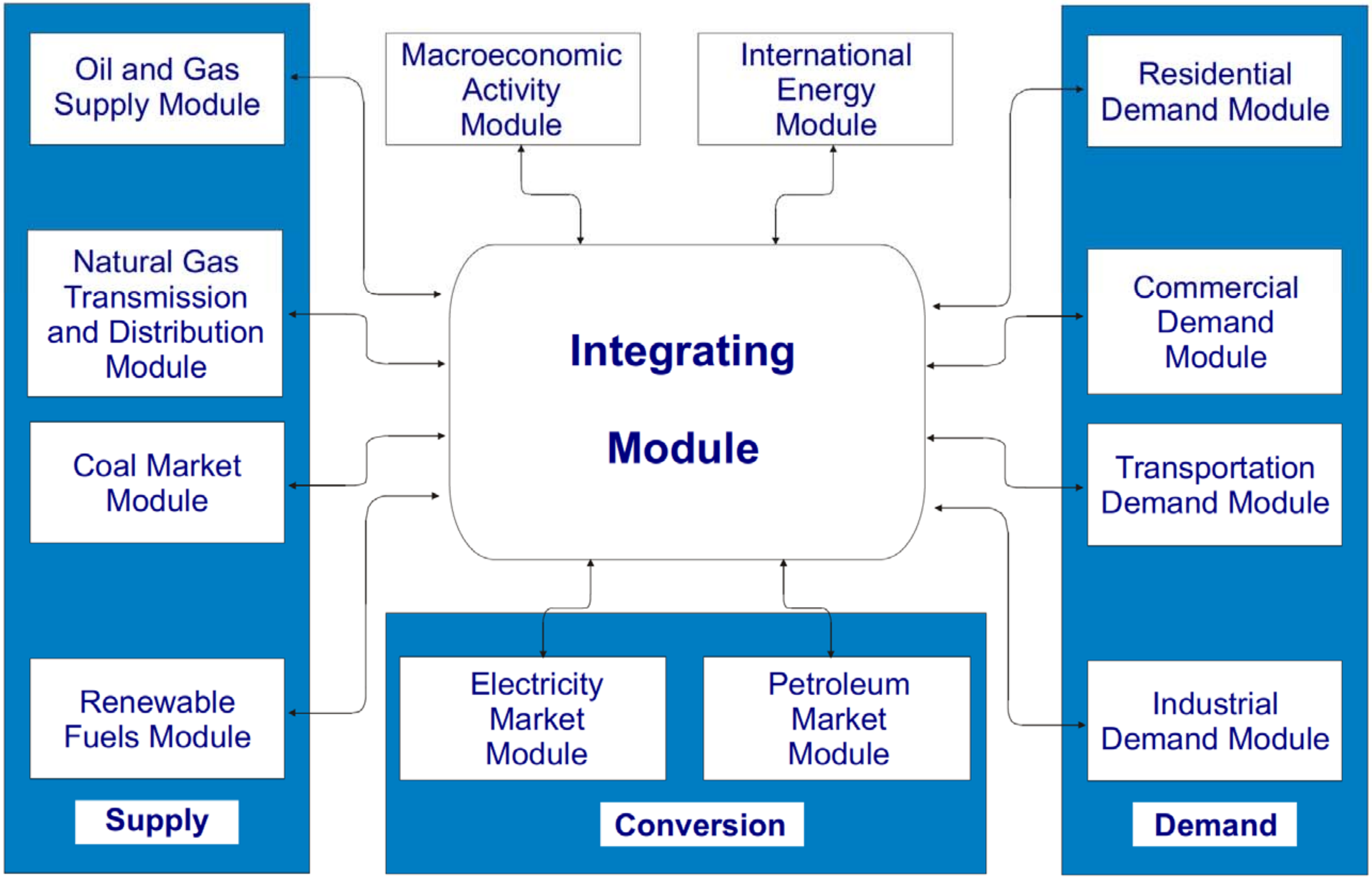
Source: IEA (2008a)

Representing technological change in energy-economic models

Technology change is modeled in many ways

- Exogenous (function of time)
  - time profile of specified cost and performance characteristics for specific technologies
  - time trend in efficiency and/or cost improvements
- Endogenous (function of variables that respond to markets/policies)
  - learning-by-doing (costs fall with cumulative production)
  - price-induced (technologies can be accelerated by higher prices)
  - R&D-driven (R&D drives cost and performance improvements)
- Treatment of technological change depends in part on the overall structure of the model
  - highly aggregate models vs. those with rich technological detail

National Energy Model System (NEMS)



Technology representation in NEMS

- Explicit technology representations (efficiencies, capital, and O&M costs, capacity factors, date commercial)
  - residential and commercial
  - transportation
  - electricity generation
  - natural gas transmission and distribution
  - refineries
- Indirect technology representation (time trend changes)
  - oil, gas and coal supply
  - industrial sector demand - except for new cogen & motors

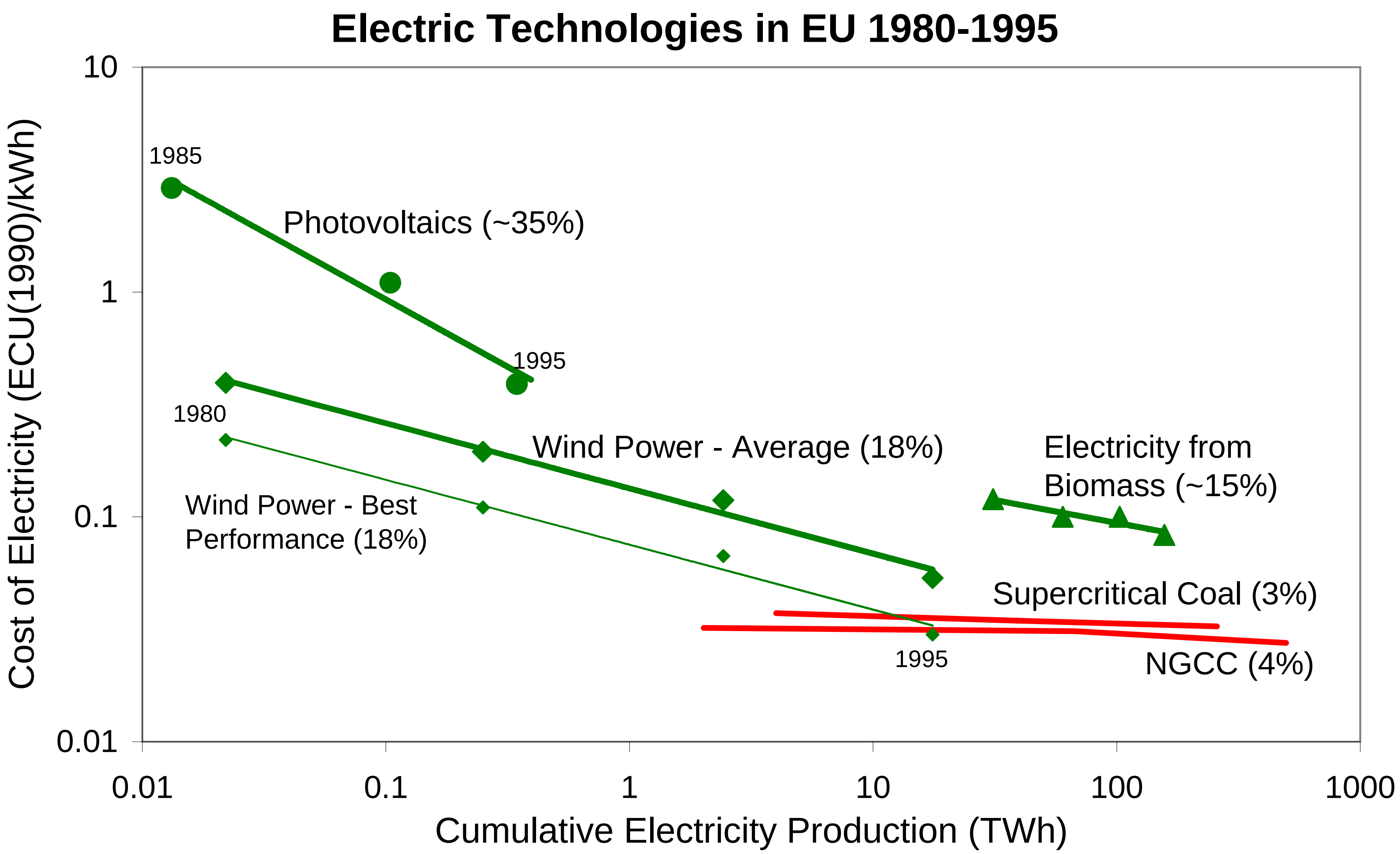
NEMS learning curves for electricity capacity expansion

- Literature largely uses simple curve
  - Overnight Cost (C) = a function of cumulative capacity (Q): $C(Q) = a * Q^{-b}$
- Progress Ratio (pr): defines speed of learning

  f = % cost decline with doubling of cumulative capacity

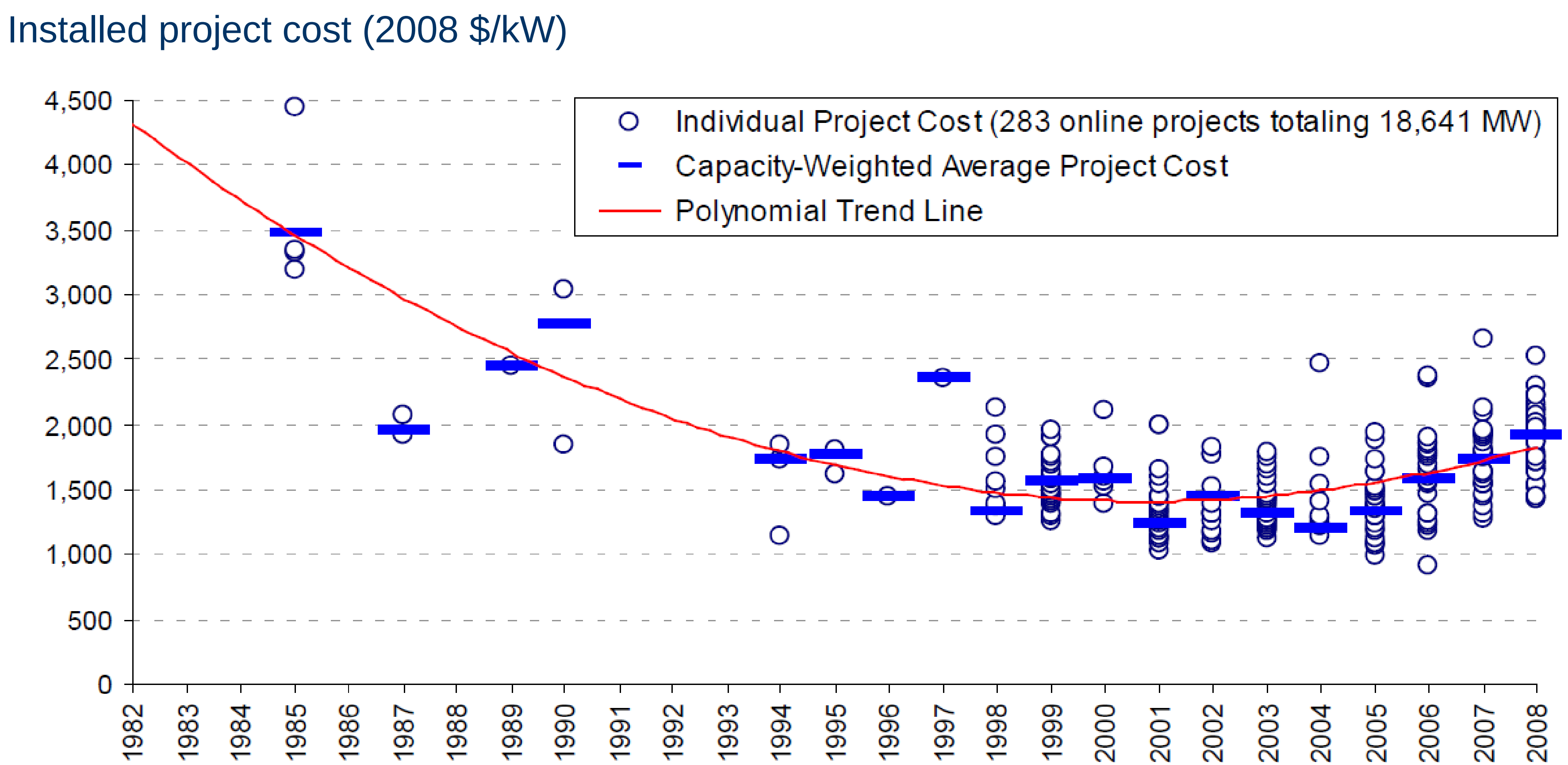
  $pr = 2^{-b} = (1 - f)$
- Issues
  - revealed values are largely prices, not costs, so other missing factors can create potential bias in estimated relationships
  - confounding factors such as economies of scale, contemporaneous R&D, changes in market structure
  - greatest price / cost distortions occur during early commercialization

New emerging technologies typically have larger learning rates than more mature technologies



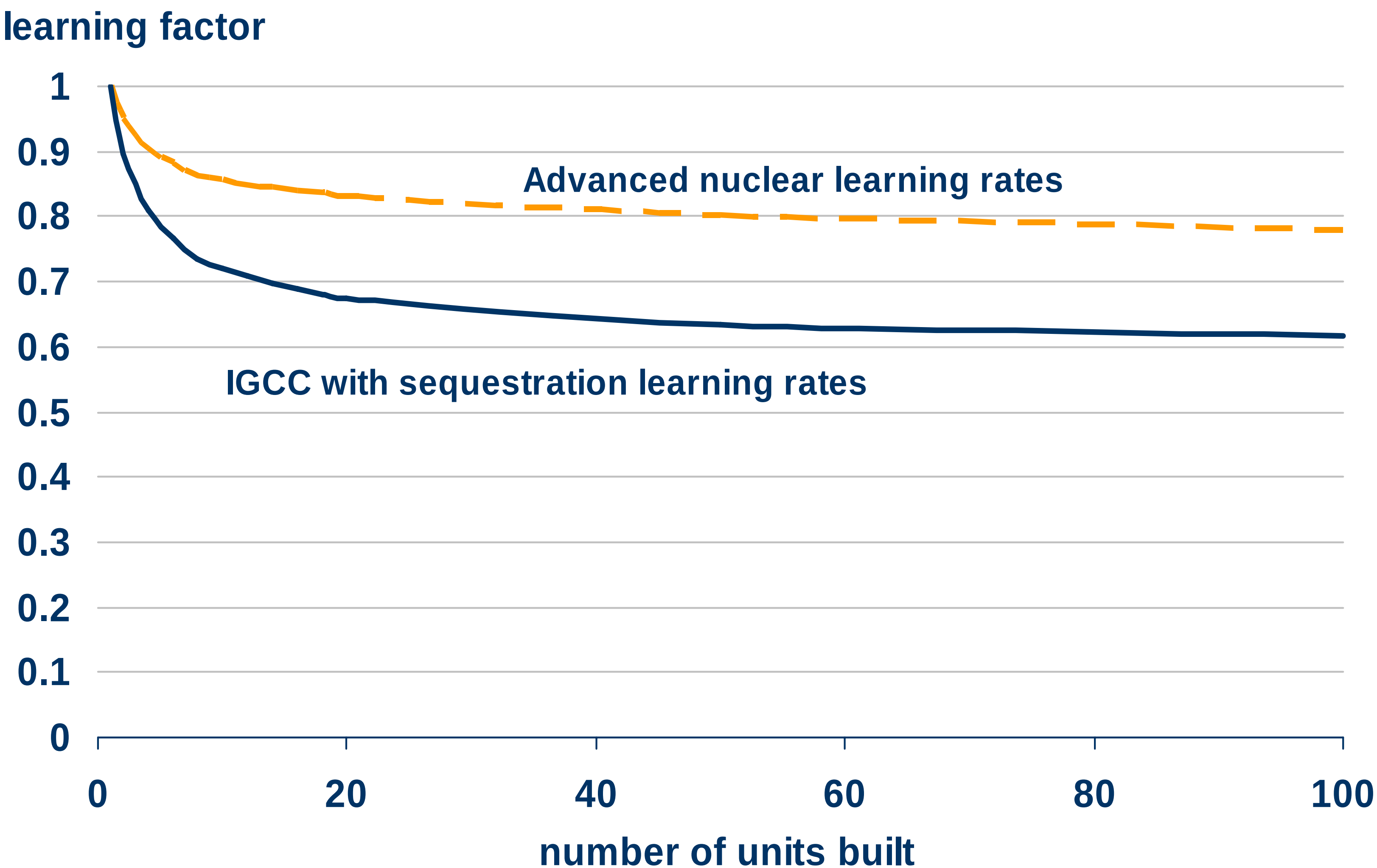
Source: Experience Curves for Energy Technology Policy, IEA/OECD 2000

Installed wind project costs have increased during past 10 years for reasons beyond technology learning



Source: DOE LBNL 2008 Wind Technologies Market Report

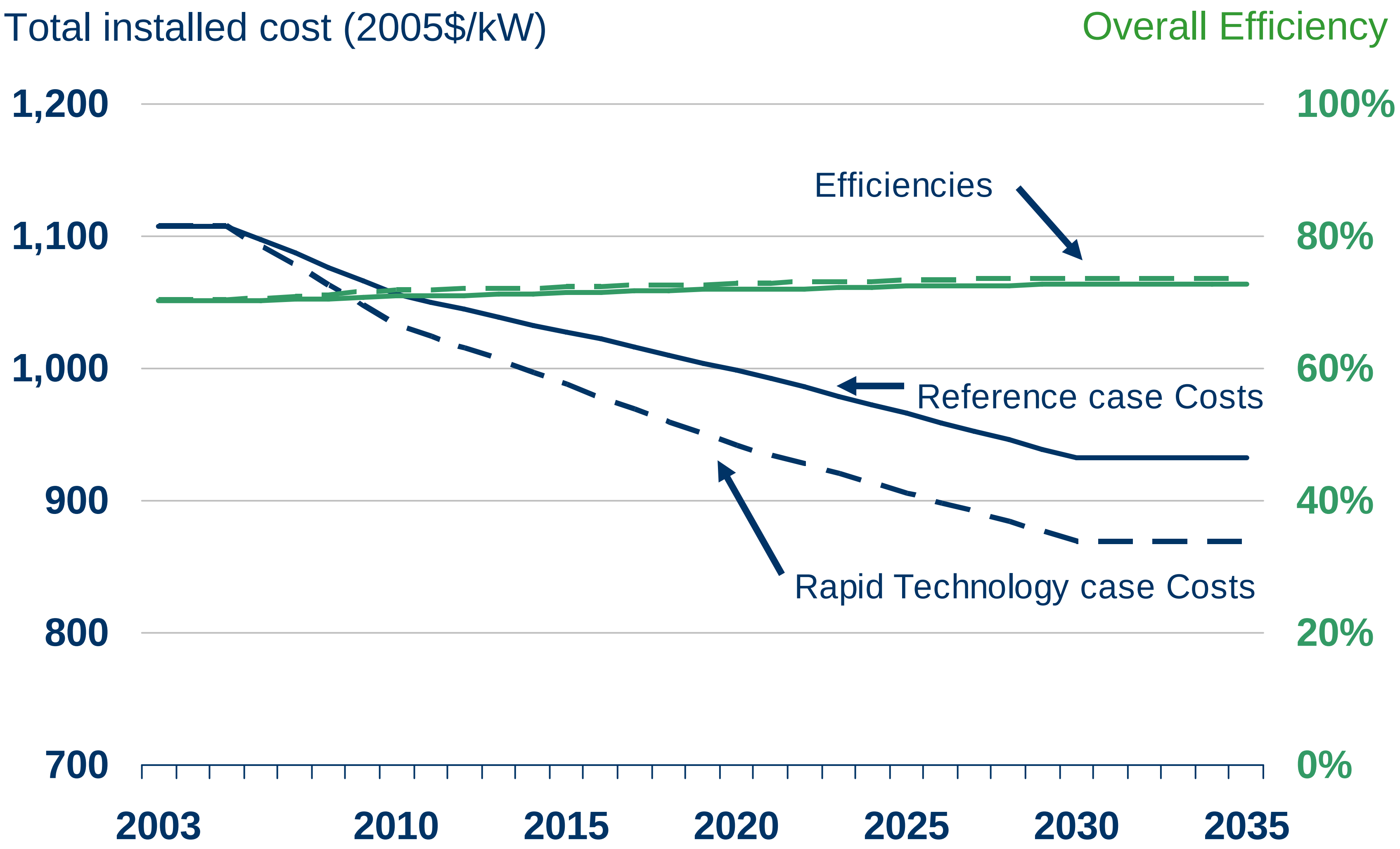
Sample learning curves from NEMS



Source: side case based on EIA AEO2010 Reference case

J3

Combined heat and power costs decline, while additional efficiency gains are small



J3 talk with Elizabeth about what is driving costs for CHP down.
JS5, 5/3/2010

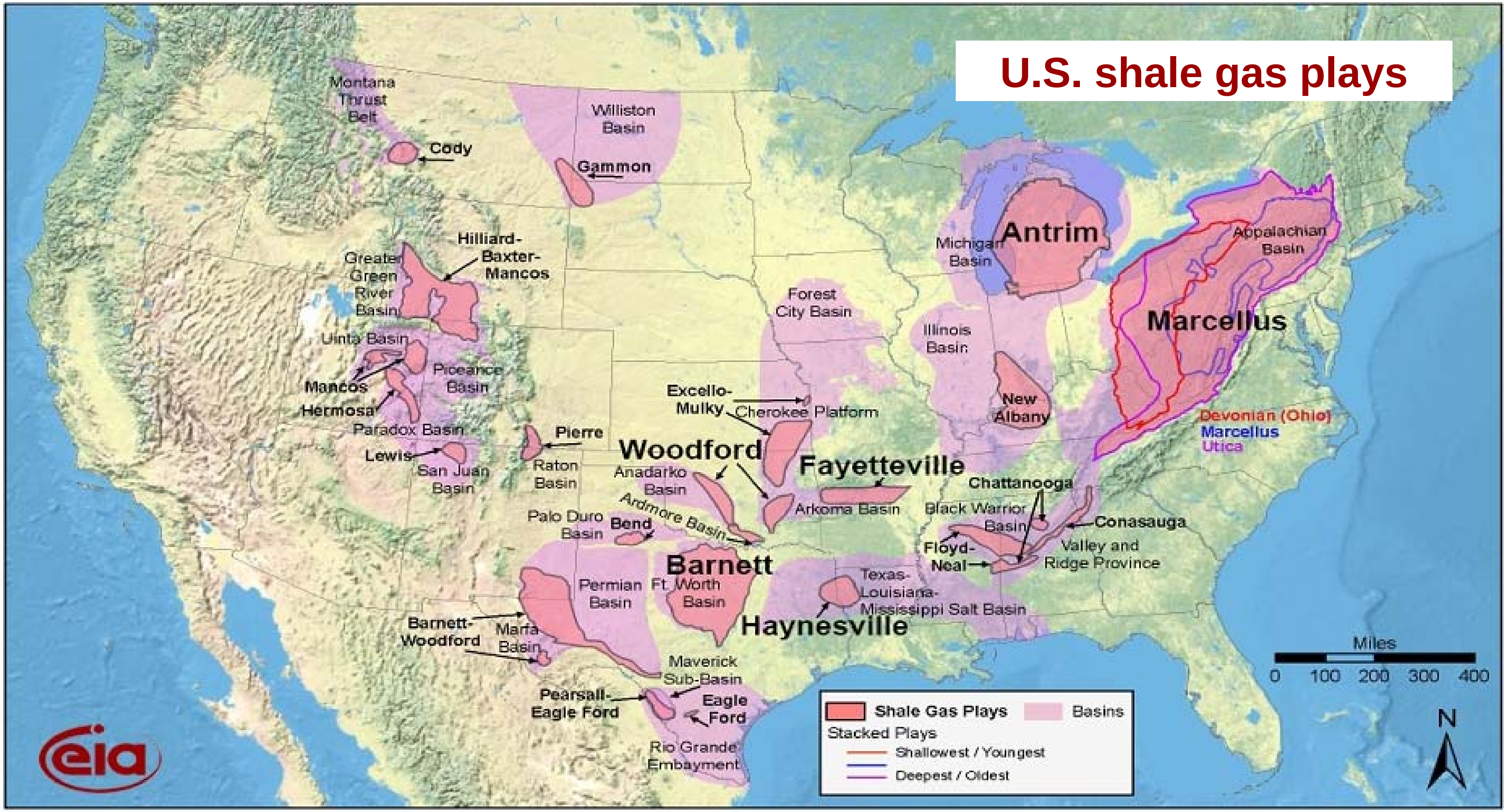
Key drivers of technological change in energy modeling

Key drivers for energy technology change

- Market drivers
  - energy prices
  - technology costs
  - consumer and investor behavior
  - demand for energy services
- Government standards
  - fuel economy, appliance efficiency, and building standards
  - renewable fuel standards, renewable electricity portfolio standards
- Government financial incentives
  - production tax credits and investment tax credits
  - loan guarantees
- Emissions policies
  - cap-and-trade or emission fee policies
- Research and development effort by public and private sectors

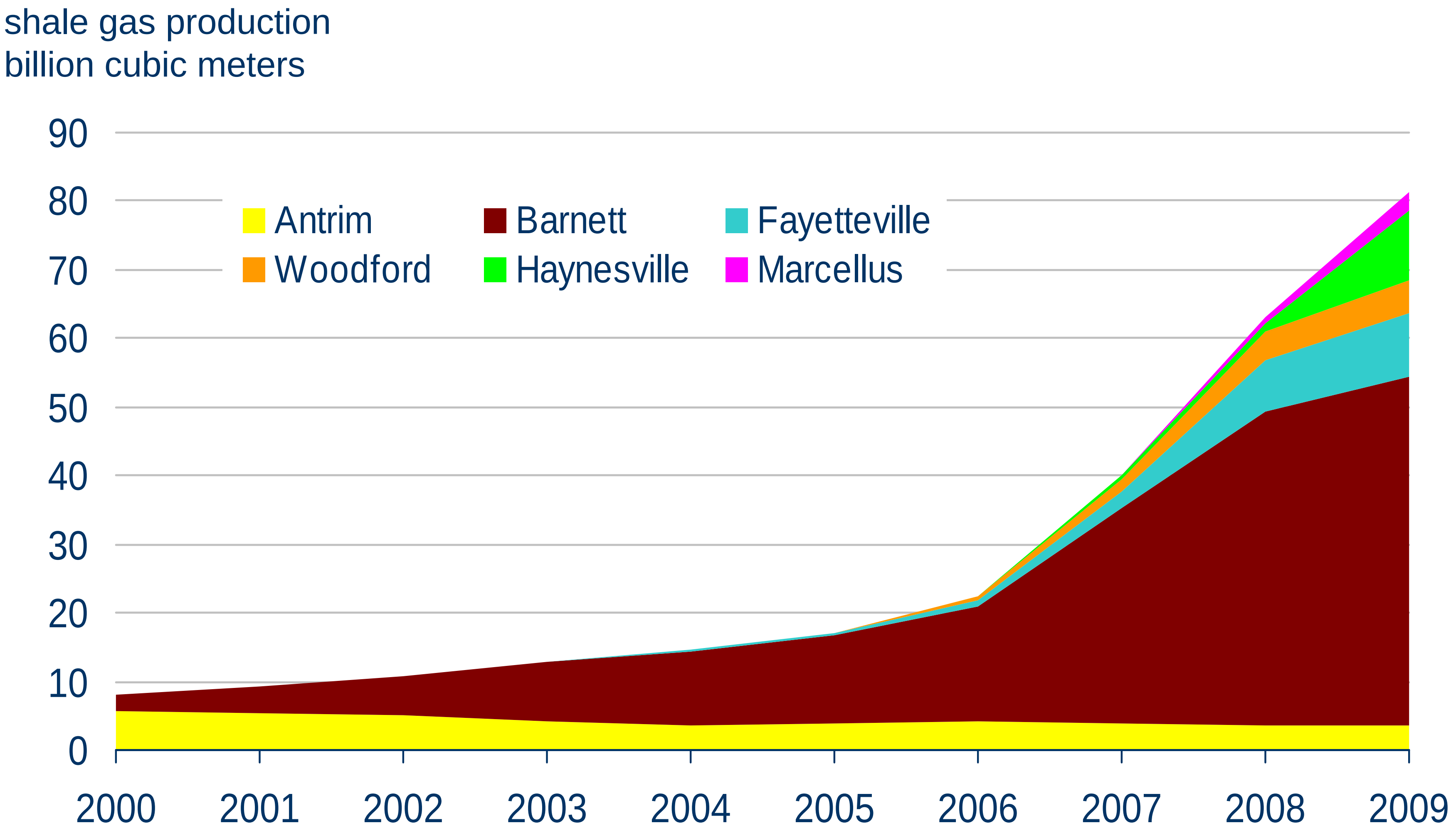
Market drivers

Success in the Barnett prompted companies to look at other shale formations in the U.S.



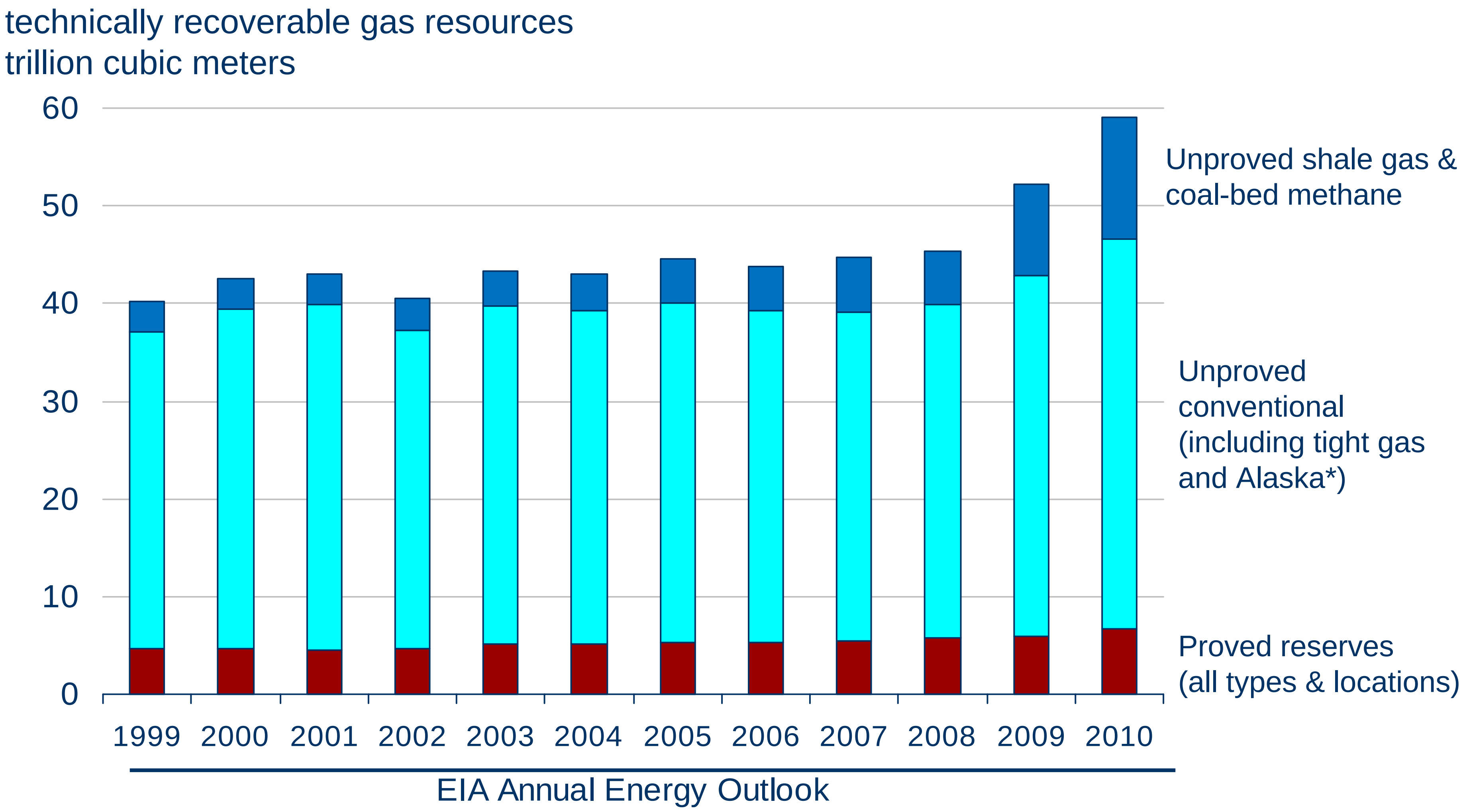
Source: Energy Information Administration based on data from various published studies
Updated: May 28, 2009

Over the last decade, U.S. shale gas production has increased 8-fold



Source: EIA, Lippman Consulting (2009 estimated)

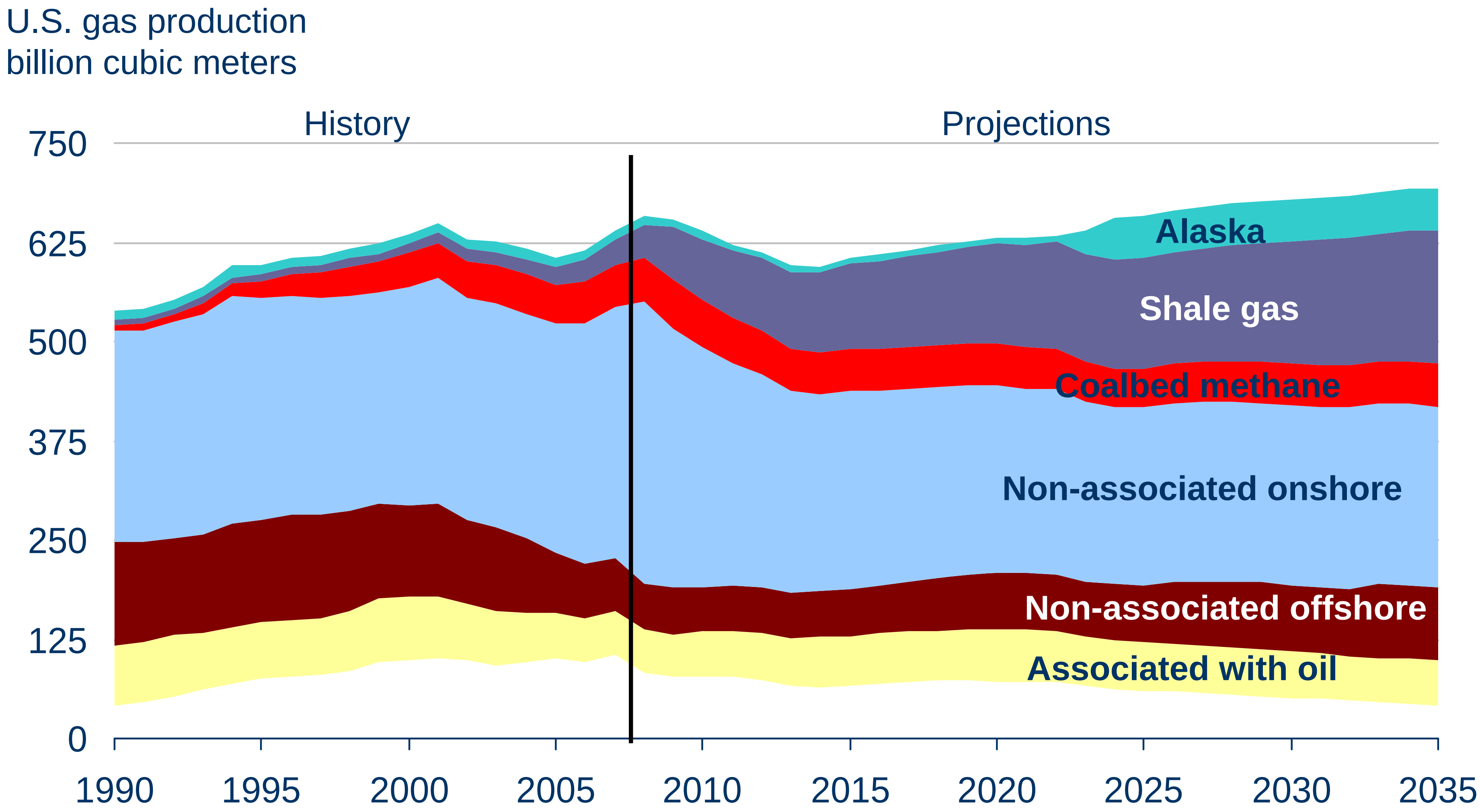
Shale gas has been the primary source of recent growth in U.S. technically recoverable natural gas resources



* Alaska resource estimates prior to *AEO2009* reflect North Slope resources not included in previously published documentation.

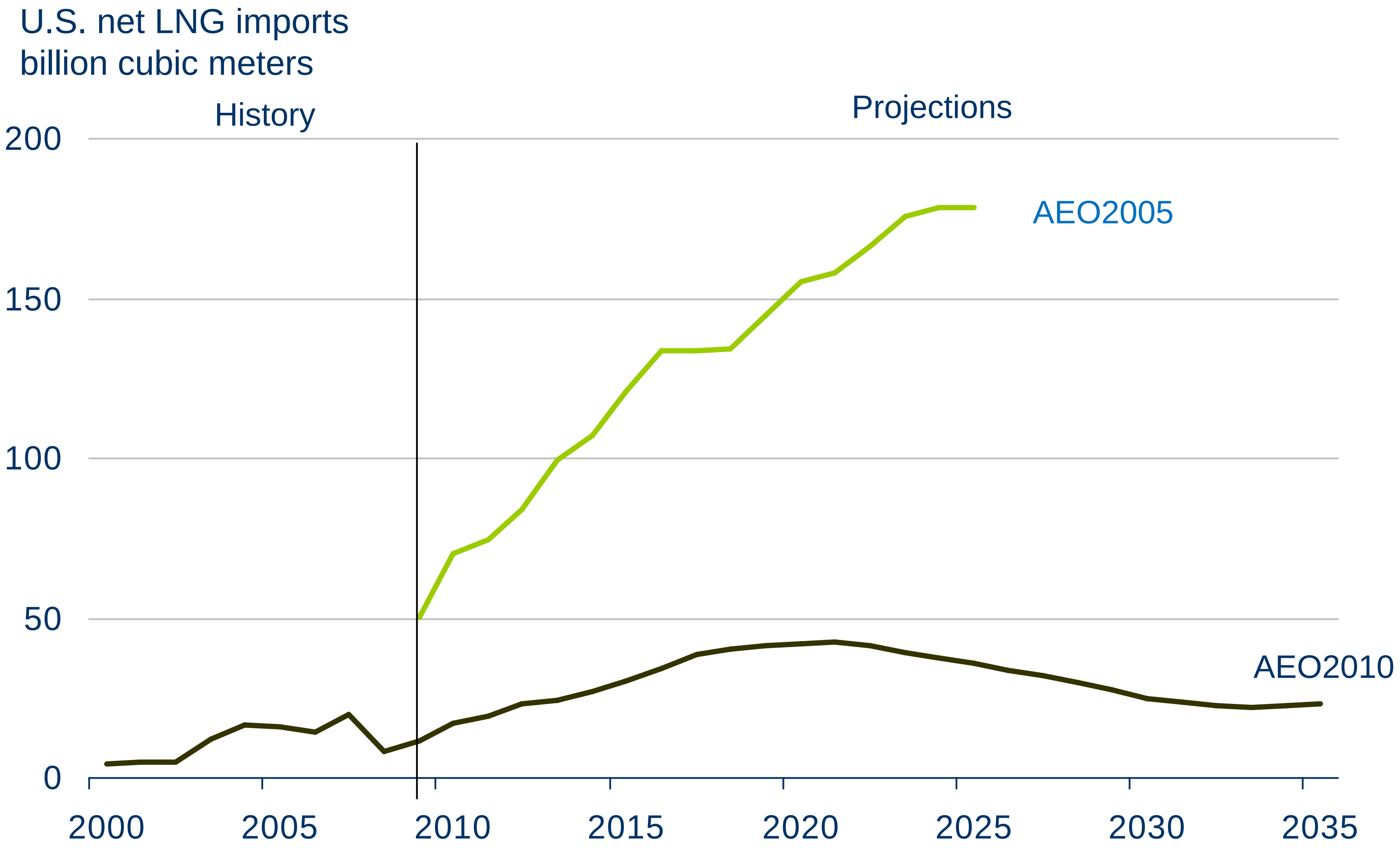
Source: U.S. Geological Service, Mineral Management Service, private data, EIA.

EIA expects shale gas and Alaska production increases to more than offset declines in other supplies



Source: EIA, *Annual Energy Outlook 2010*

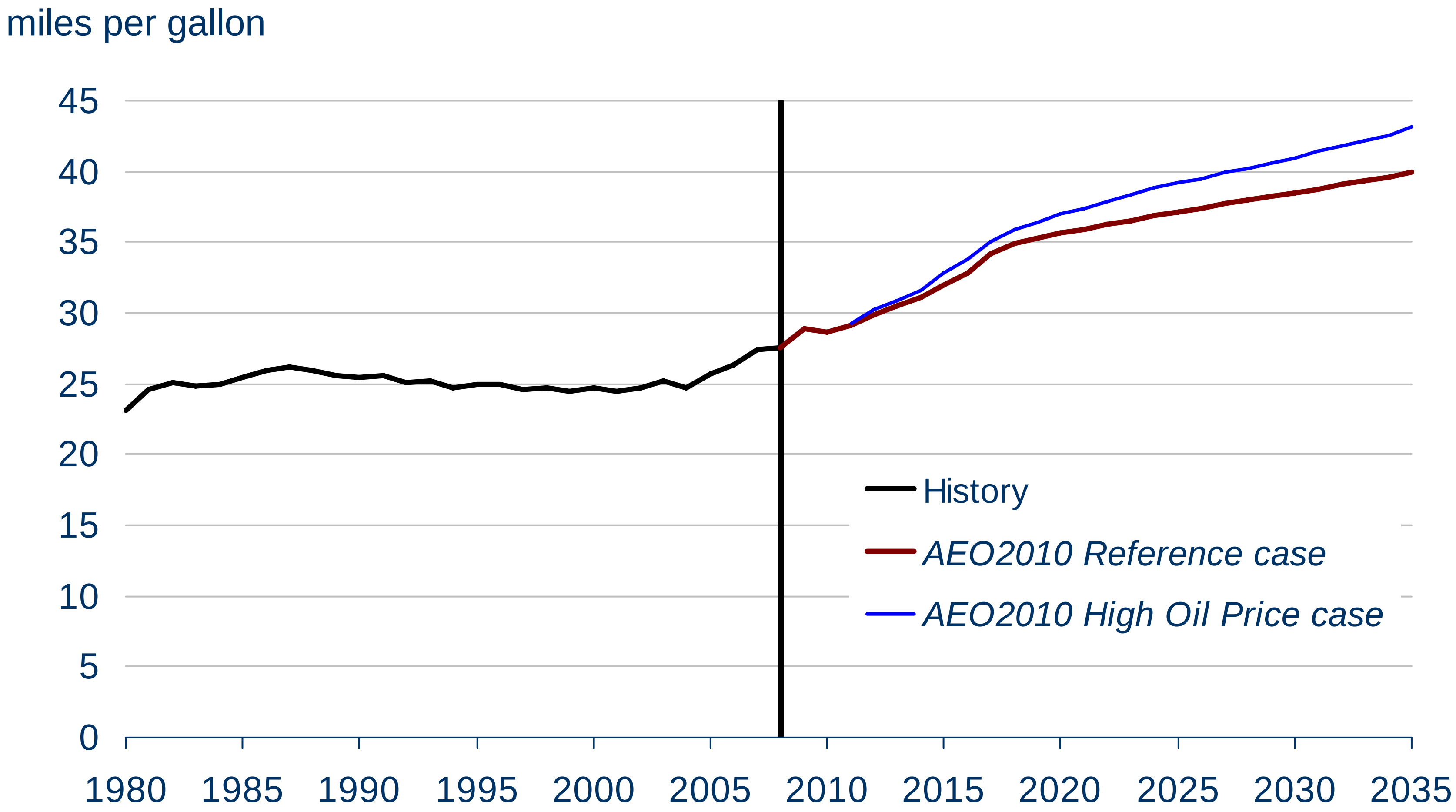
Over the past 5 years, EIA has significantly lowered its projection of LNG imports into the U.S.



Source: EIA, Annual Energy Outlooks

Government standards

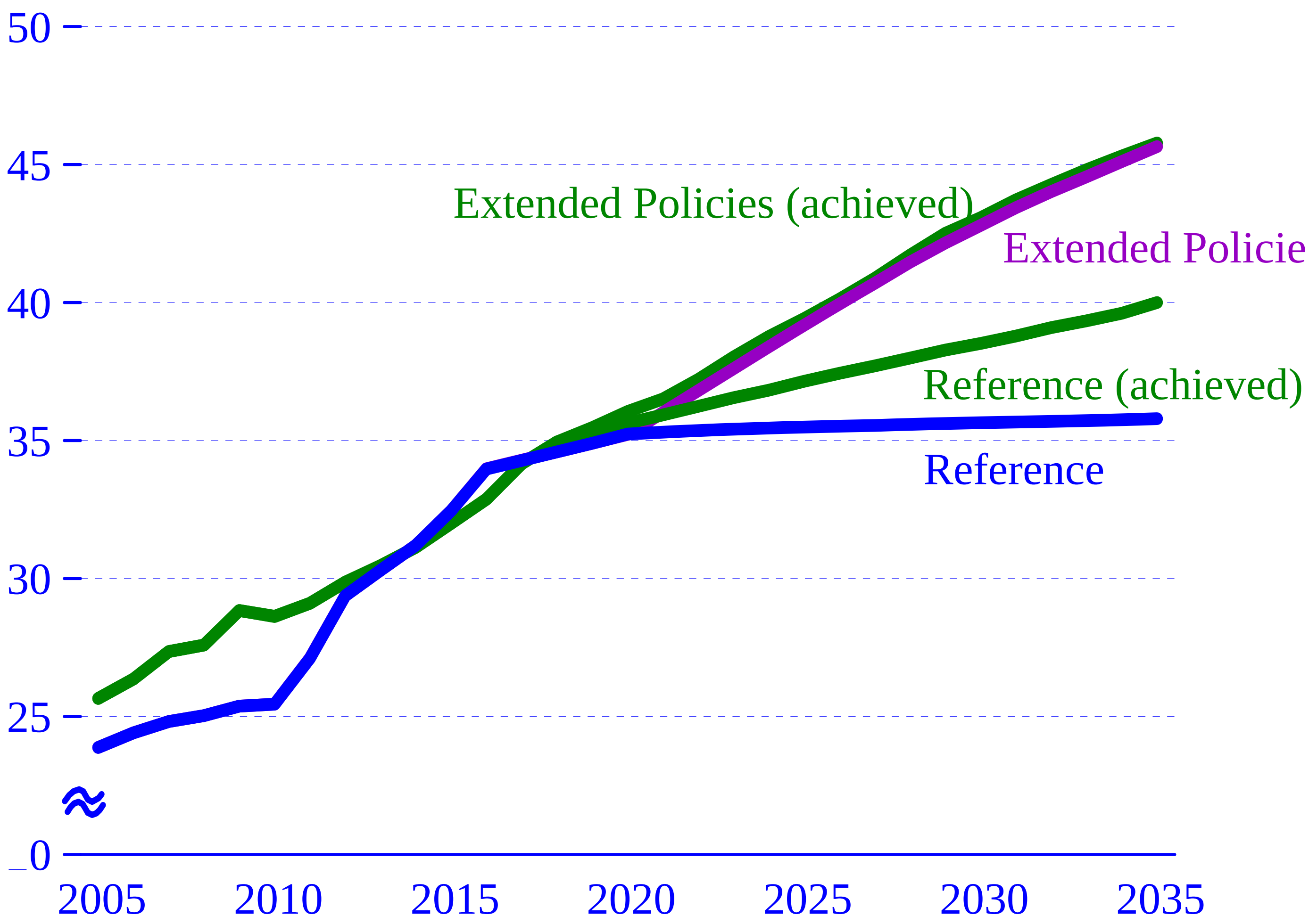
New light duty vehicle efficiency reaches 40 mpg by 2035



Source: *Annual Energy Outlook 2010*

The continuation of existing policies into the future would increase vehicle fuel economy

Figure 10. New light-duty vehicle fuel efficiency standards and fuel efficiency achieved in two cases, 2005-2035 (miles per gallon)



Changes in the adoption of efficient residential and commercial technologies significantly affect projections; new uses play a key role in projected demand growth

Figure 42. Residential delivered energy consumption per capita in four cases, 1990-2035 (index, 1990 = 1)

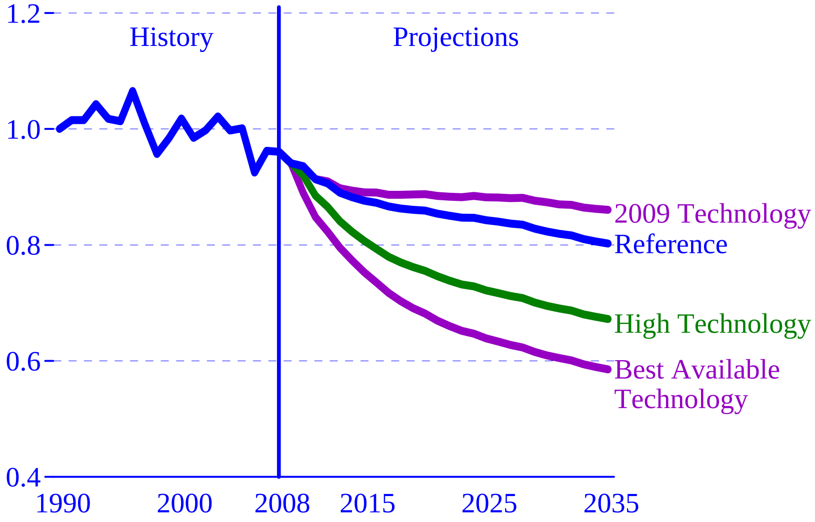
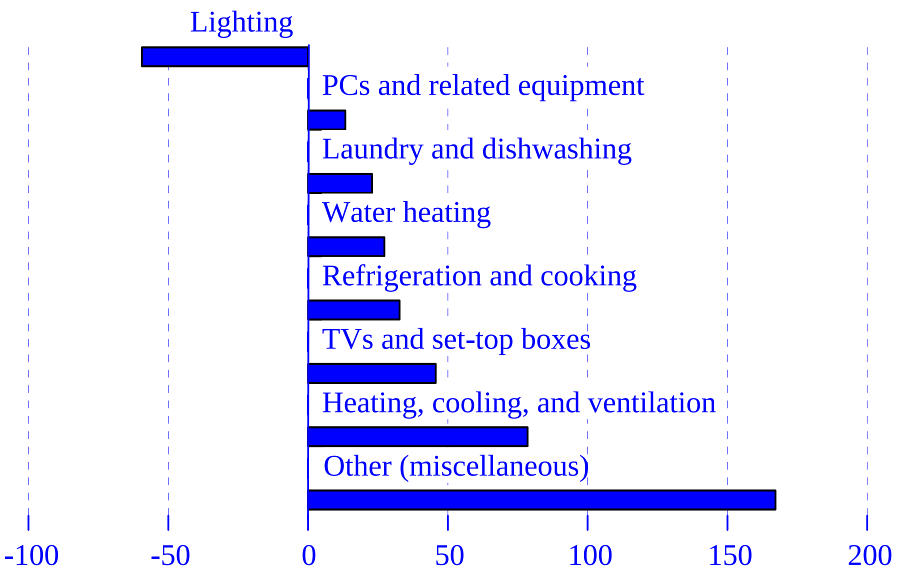
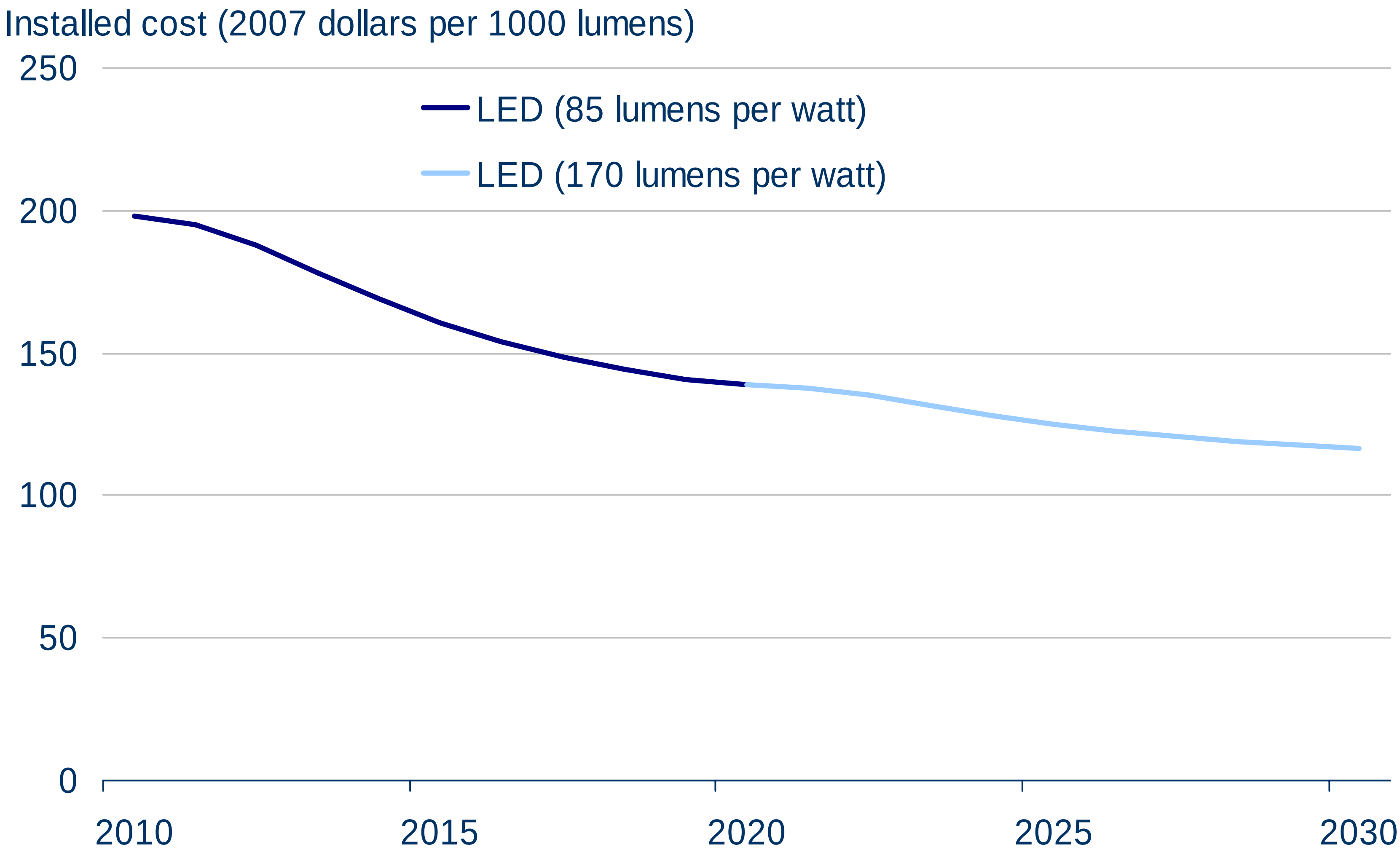


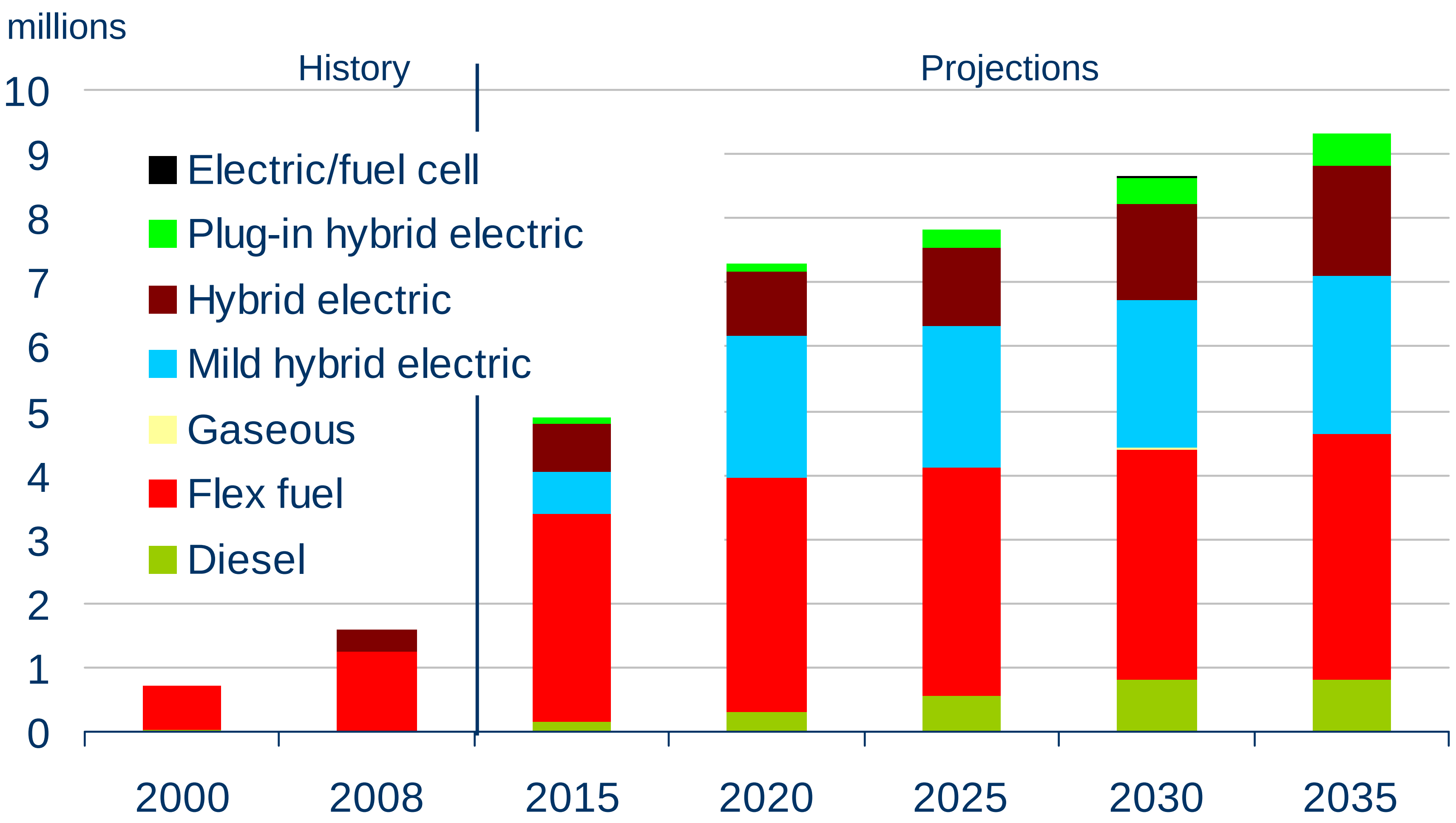
Figure 43. Change in residential electricity consumption for selected end uses in the Reference case, 2008-2035 (billion kilowatthours)



Example of both market and regulatory induced technology change: commercial sector LED lighting



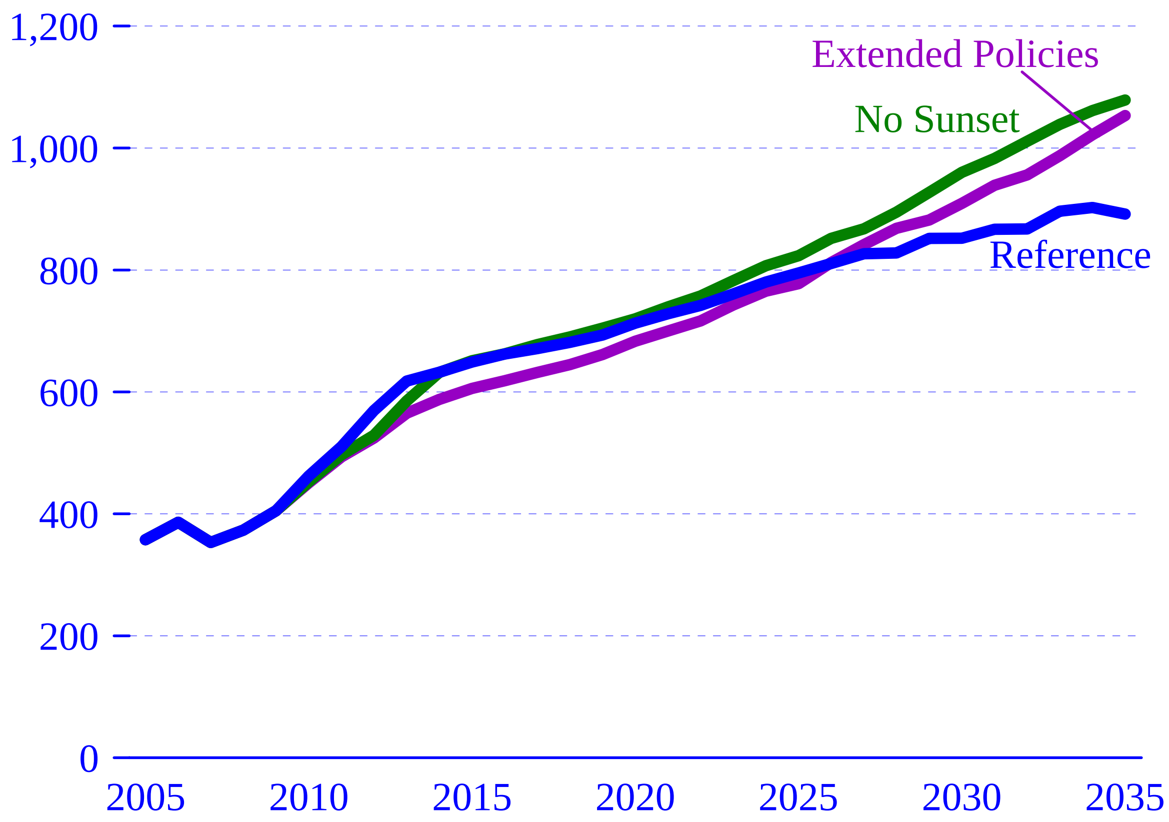
Mild and full hybrid systems dominate new light-duty vehicle sales by 2035



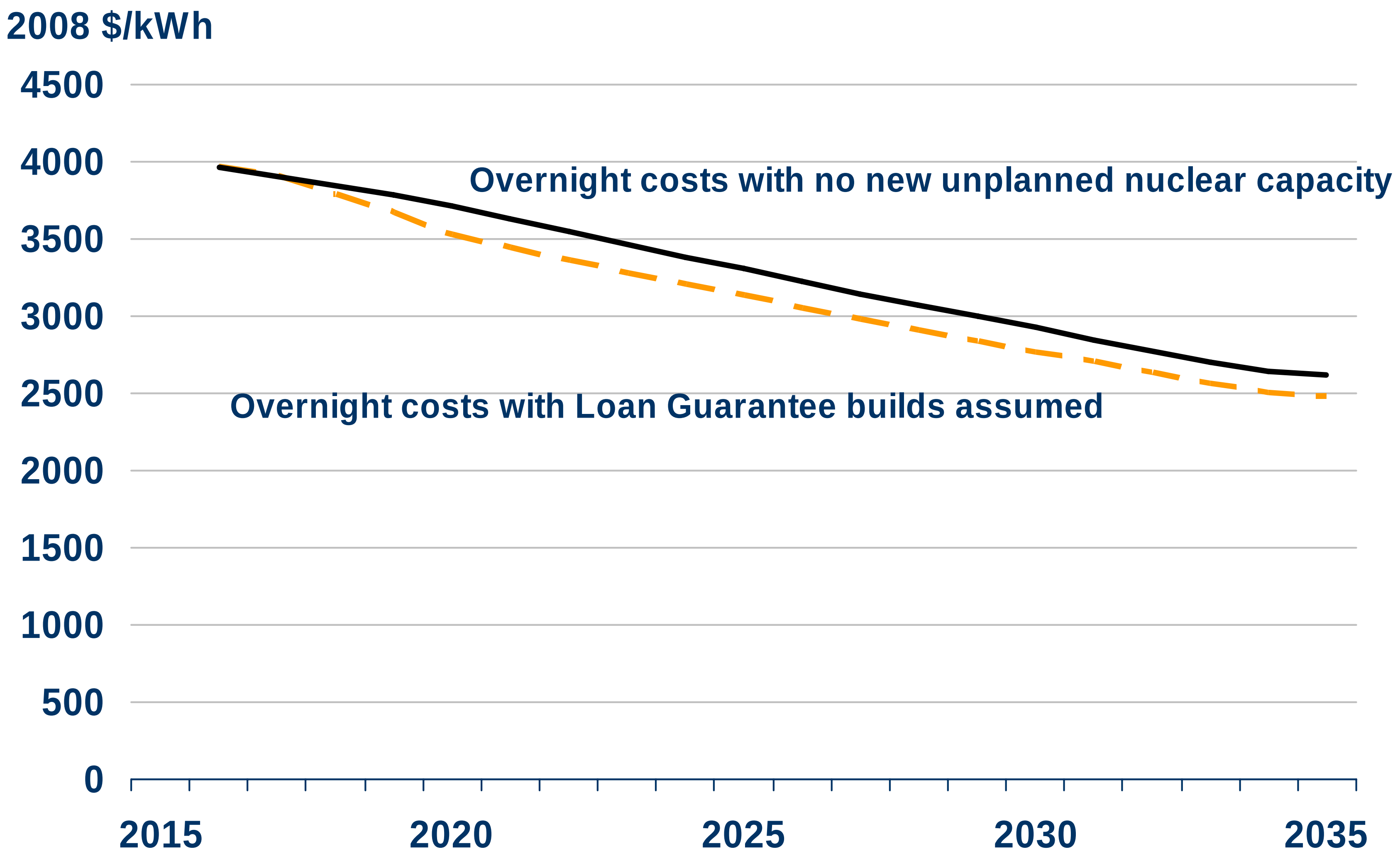
Government financial incentives

The continuation of existing policies into the future increases renewable generation

Figure 11. Renewable electricity generation in three cases, 2005-2035 (billion kilowatthours)



Advanced nuclear overnight costs are lower with loan guarantees



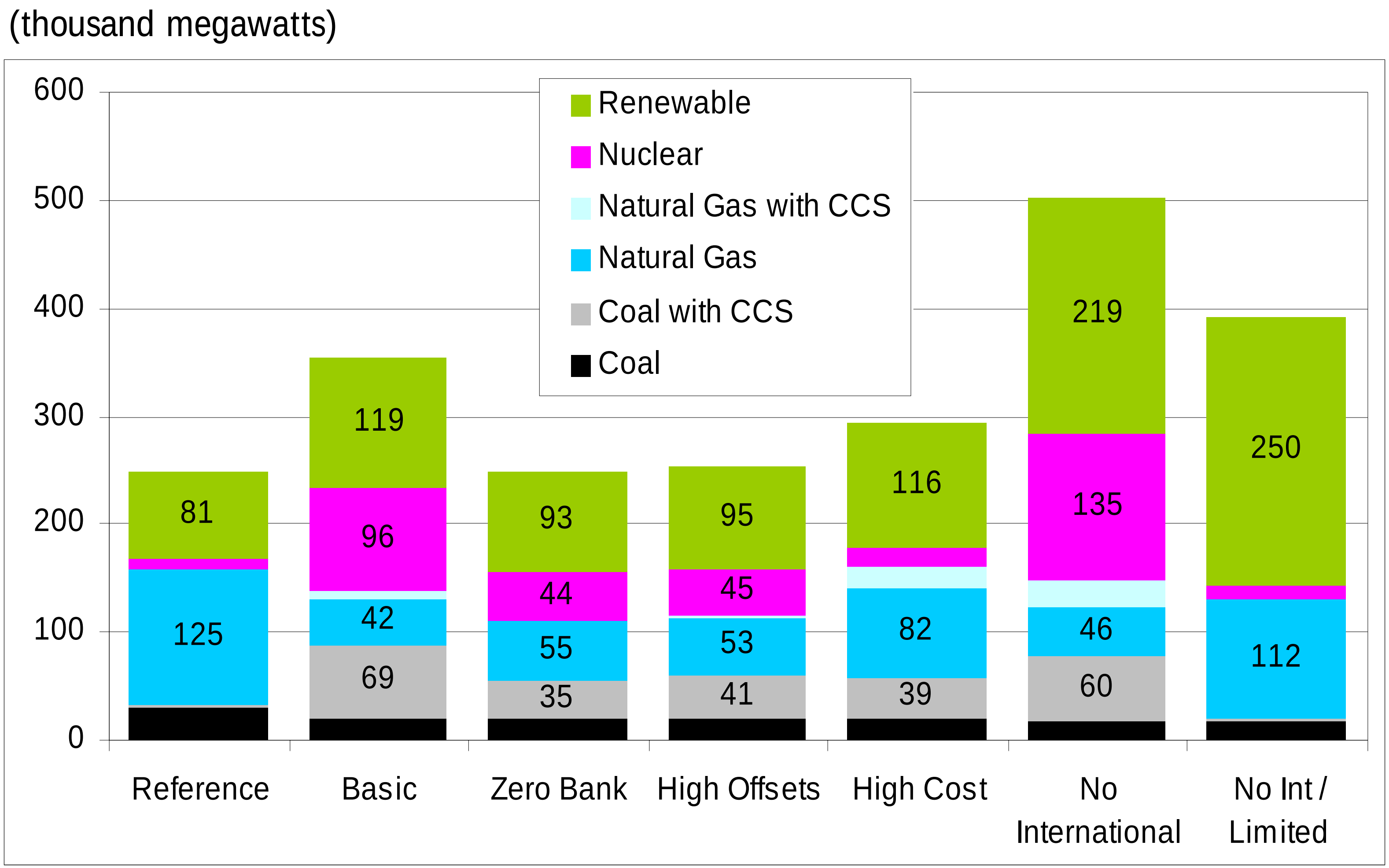
Source: side case based on EIA AEO2010 Reference case

Emissions policies

A Carbon Policy: A Carbon Policy Example: Main Cases

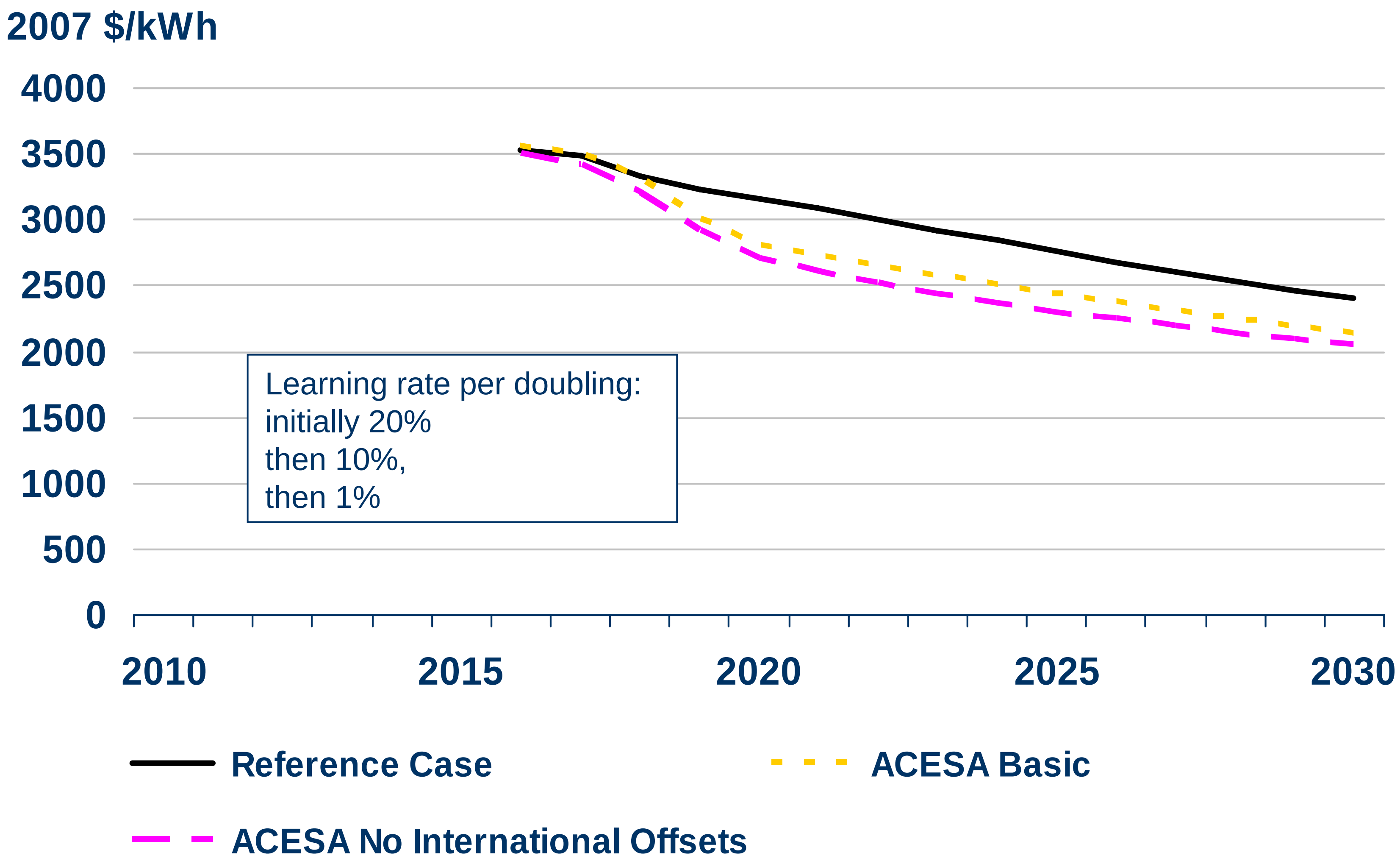
Case Name	Assumptions
Reference	*Updated AEO2009* Reference Case, which includes the provisions of the American Recovery and Reinvestment Act (ARRA).
Illustrative Policy Cases	
Basic	Integrated analysis of all of the modeled provisions of Hr. 2454(ACESA). Build allowance bank through 2030 to use thereafter.
No International Offsets	Same as Basic but assumes international offsets are too expensive or unable to meet the certification requirements for use.
No International / Limited Tech	Same as Basic but limits additions of new nuclear, fossil with CCS and biomass gen to reference case levels. Also no international offsets.

Example of carbon policy impact on capacity additions, 2008 to 2030



Capacity additions parallel the behavior of the change in the fuel mix in generation.

Overnight costs of new coal with sequestration plants (CCS) show learning over time



AEO2010 includes 38 sensitivity cases

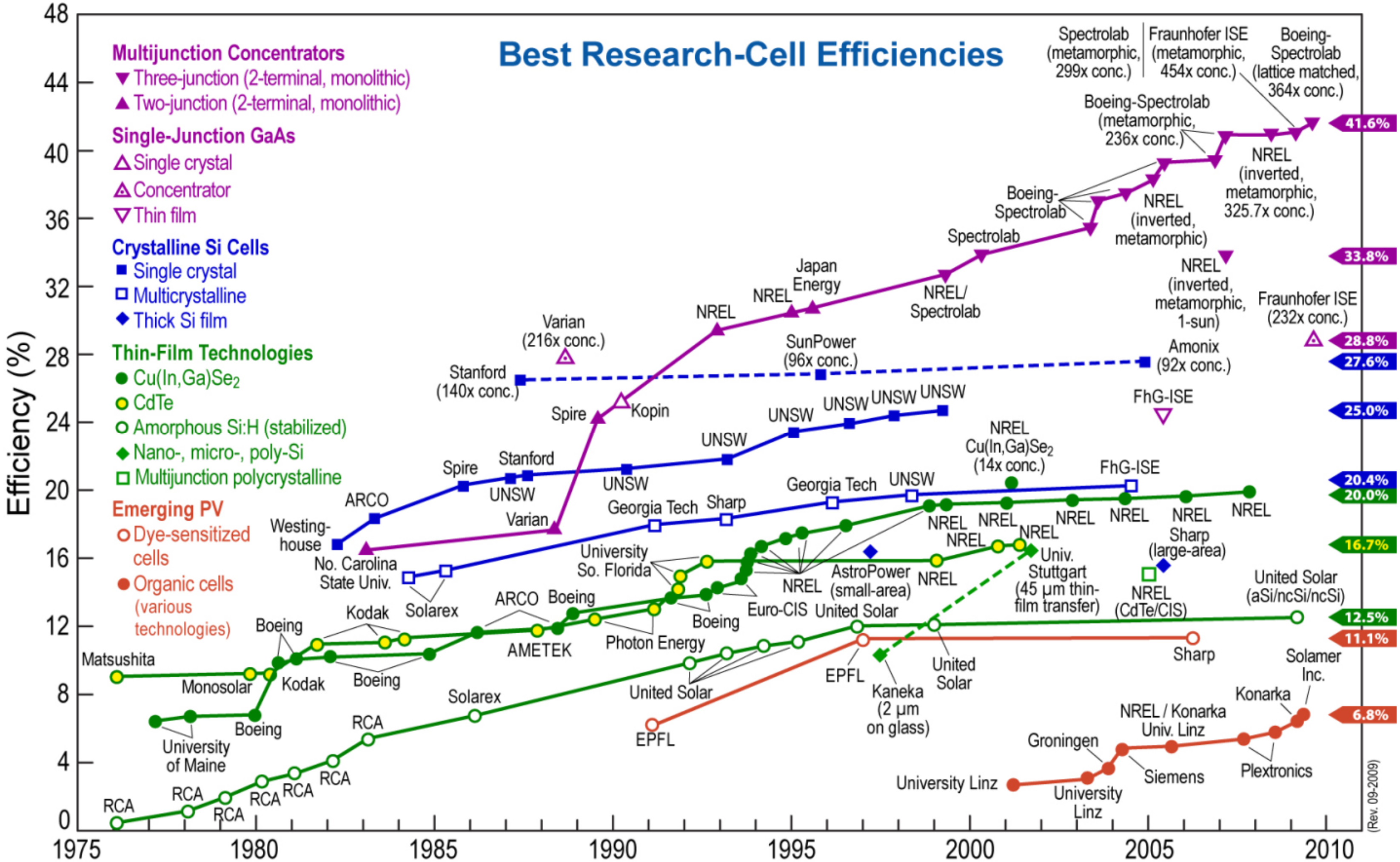
AEO2010 Case	# of cases	Description
Reference		EIA’s starting point for projections through 2035
Economic Growth	2	Lower and higher economic growth scenarios. Average annual rate of GDP from 2008 to 2035 is 1.8 percent (Low case) or 3.0 percent (High case) compared to 2.4 percent in the Reference case
Oil Price	2	World light sweet crude prices in 2035 in 2008 dollars are $51 per barrel (Low case) or $210 per barrel (High case) compared to $133 per barrel in the Reference case
Residential/Commercial Technology	6	A 2009 Technology case (freezes existing shell performance and equipment menu) that is less optimistic about efficiency than the Reference case and two cases (High Technology and Best Available Technology) that are more optimistic than the Reference case
Industrial technology	2	A 2010 Technology case and a High Technology case that are, respectively, less and more optimistic than the Reference case
Transport technology	2	Alternatives that lower and raise the projected cost of vehicle efficiency technologies
Electricity Technology	6	Alternatives that lower and raise the costs of fossil, renewable, and nuclear power technologies
Integrated Technology	2	Cases that apply either “High Technology” or “Low Technology” assumptions across all sectors
Natural Gas Heavy Truck Incentives	4	Vehicle, fuel, and refueling infrastructure tax credits are applied through 2019 or 2027 under “base” or “expanded” characterizations of the potential market
Availability of Shale Gas and other Low Perm Gas	3	Two cases that restrict new drilling for shale and other tight gas, and one that expands the size of the shale resource base.
High LNG supply	1	More gas is available from outside North America
Coal Price	2	Higher and lower coal prices
Oil and Gas Technology	2	Alternatives that lower and raise the pace of advances in drilling technology
No GHG concern	1	Removes risk premium on long-lived investments projects with a large GHG footprint that is included in the Reference case to reflect concern regarding future policies to limit GHGs
Existing nuclear plants retire at age 60	1	Examines impact if existing nuclear plants retire at age 60, a milestone that many units reach between 2030 and 2035.
Extended Policies and No Sunset Cases	2	Alternatives that modify the “current laws and regulations” assumption of the Reference Case

Thank you

For more information

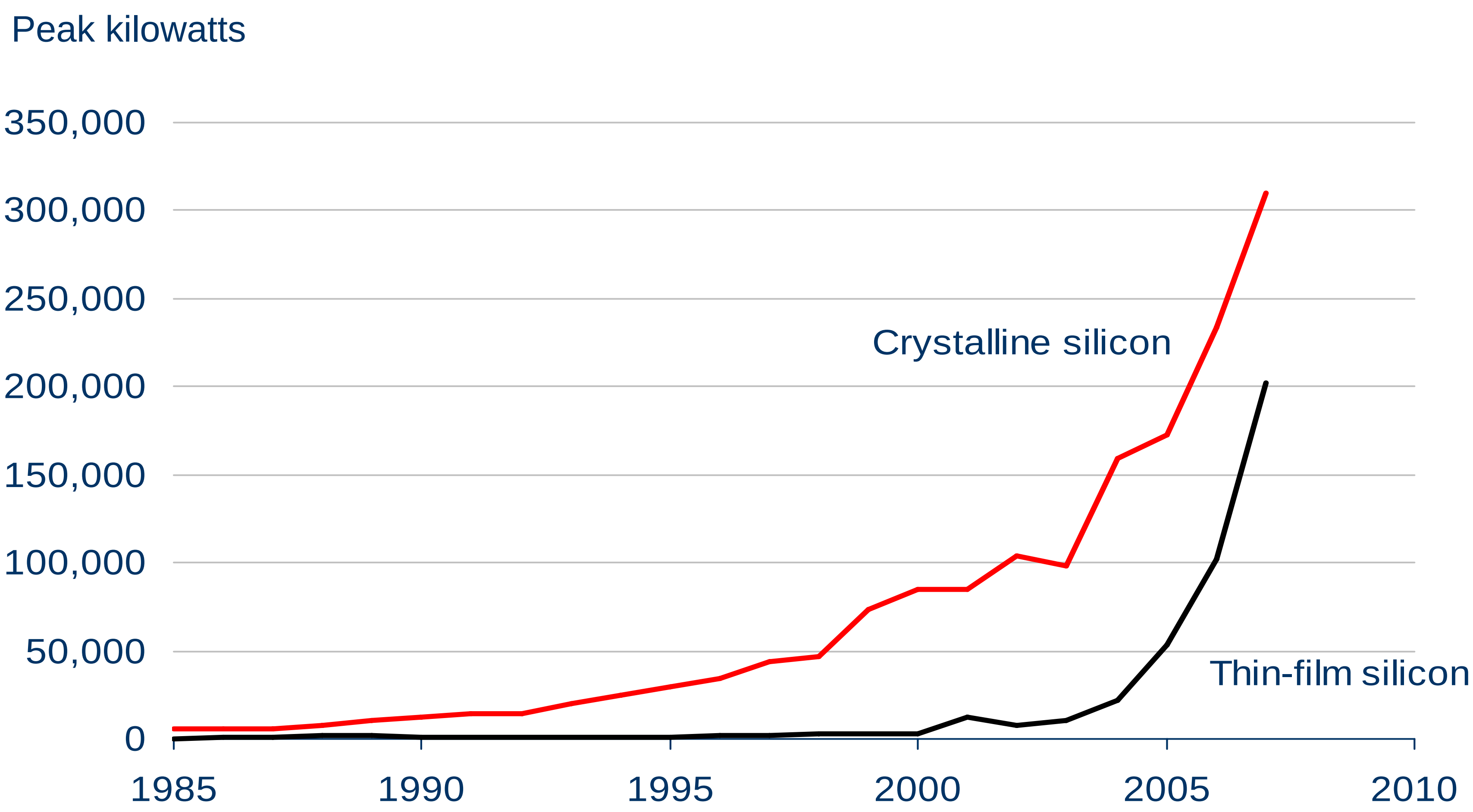
U.S. Energy Information Administration home page	www.eia.gov
Short-Term Energy Outlook	www.eia.gov/emeu/steo/pub/contents.html
Annual Energy Outlook	www.eia.gov/oiaf/aeo/index.html
International Energy Outlook	www.eia.gov/oiaf/ieo/index.html
Monthly Energy Review	www.eia.gov/emeu/mer/contents.html
National Energy Information Center	(202) 586-8800 Live expert from 9:00 AM – 5:00 p.m. EST Monday – Friday (excluding Federal holidays) email: InfoCtr@eia.doe.gov

The efficiencies of PV cells continue to increase



Source: Figure 3.6. Best research cell efficiencies 1975–2009 (Kazmerski 2009) NREL

US PV shipments

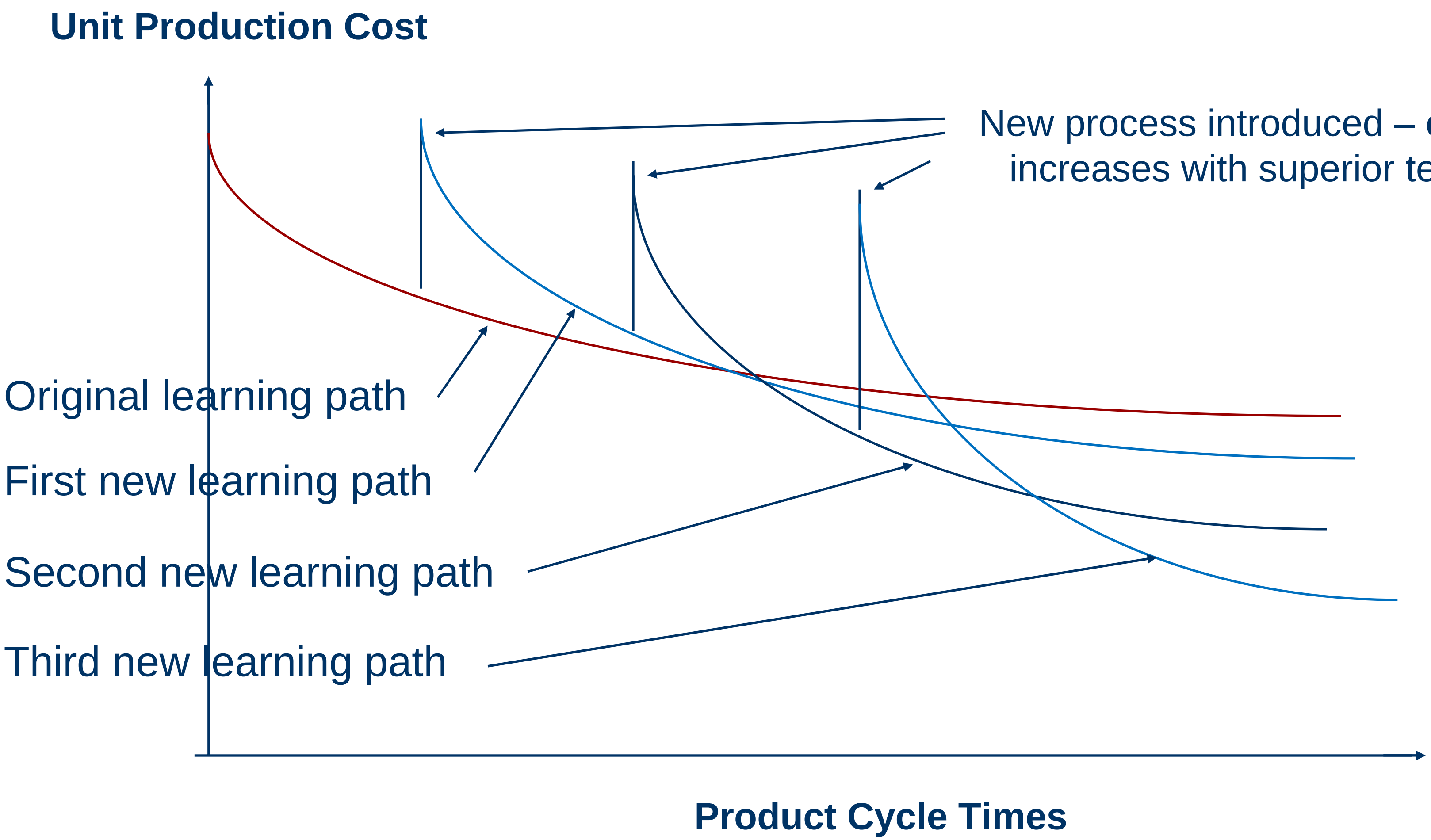


Source: *Annual Energy Outlook 2010*

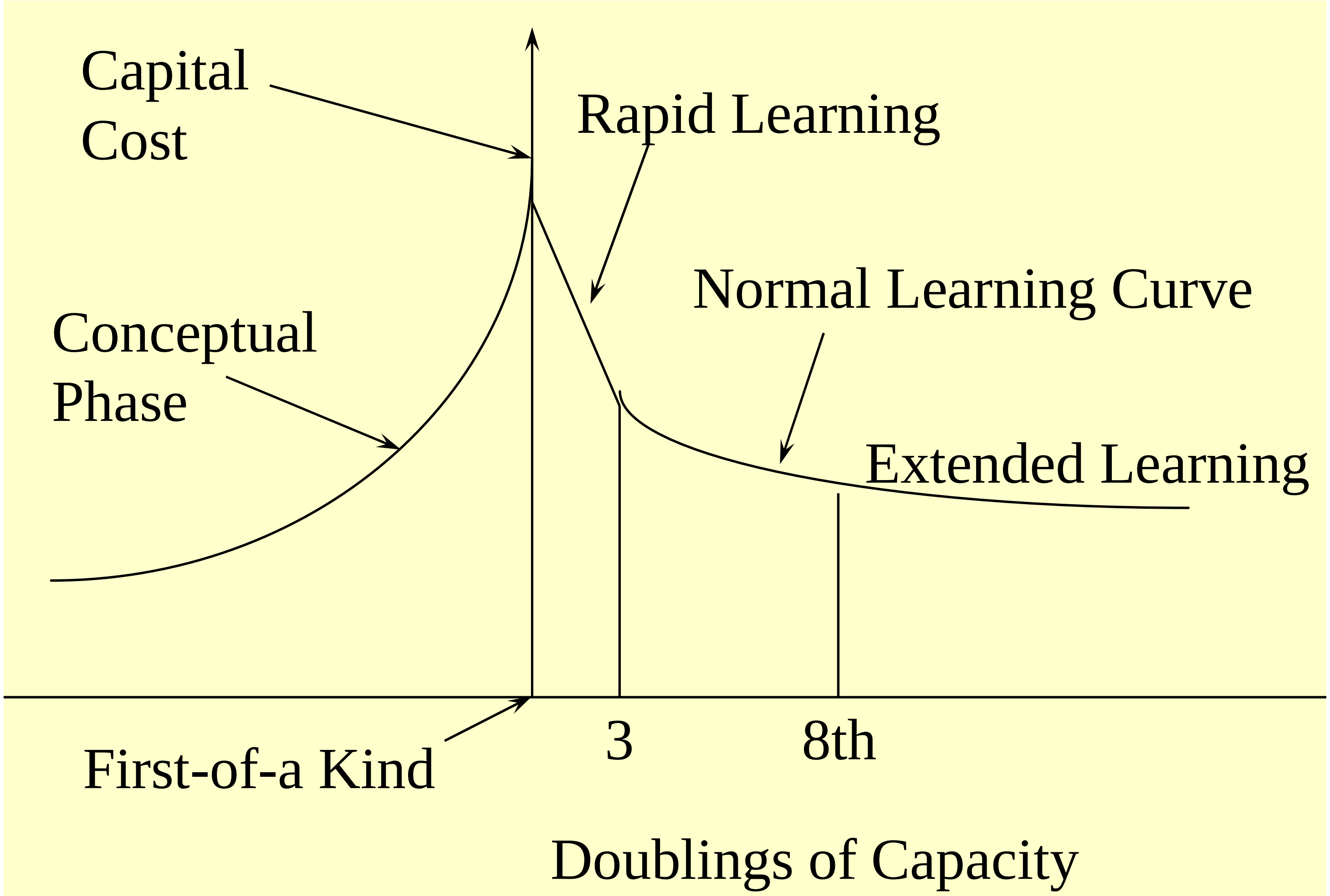
Learning-by-doing: returns to adoption

- Learning-by-doing – well documented since 1930's
- Wright (1936) – direct labor costs of manufacturing an airframe fell by 20% with every doubling of cumulative output
- Subsequent authors broadened analysis of learning to other costs and showed costs declined with experience
- Cumulative learning - combination of cumulative production plus cumulative engineering resources applied to the innovation (Hatch, Mowery 1998)
  - Always some loss of learning when transfer from R&D lab to manufacturing production line.

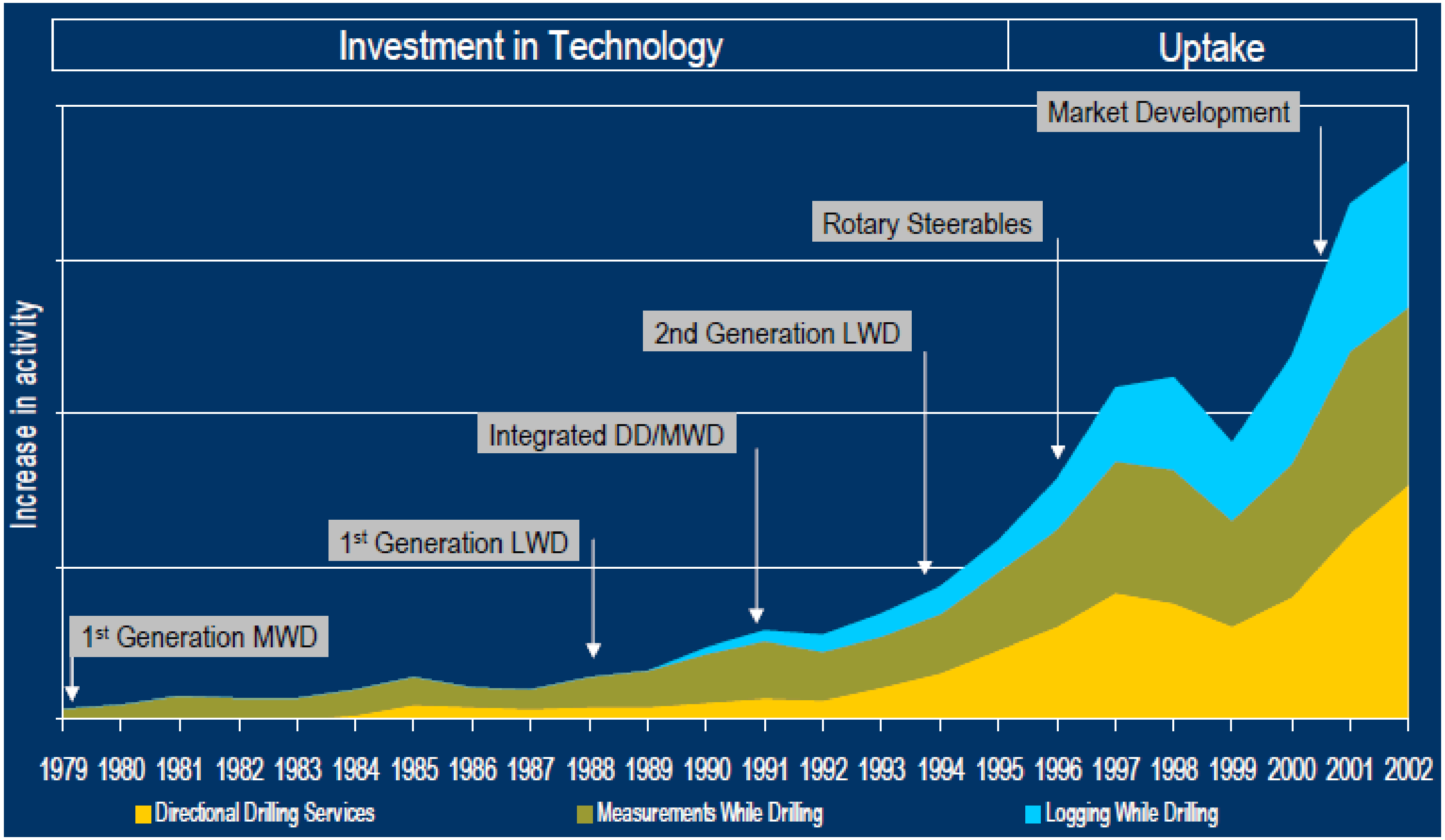
Manufacturing production costs step down with new process introduction (Mowery)



Endogenous technological learning by component – an illustrative example



Technology change starts slow then accelerates. Example: historical uptake for directional drilling



Source: Schlumberger 2007

Data sources for learning assumptions

- Model of Learning-By-Doing
  - (electricity capacity expansion) - various studies

- Specified cost and performance by year and end-use
  - (buildings and transportation) - engineering analysis, e.g., Navigant Consulting

- Time trends
  - (for oil, gas, coal, industrial sectors) - econometric / engineering analysis, e.g., Advanced Resource Int., Navigant Consulting and econometrics

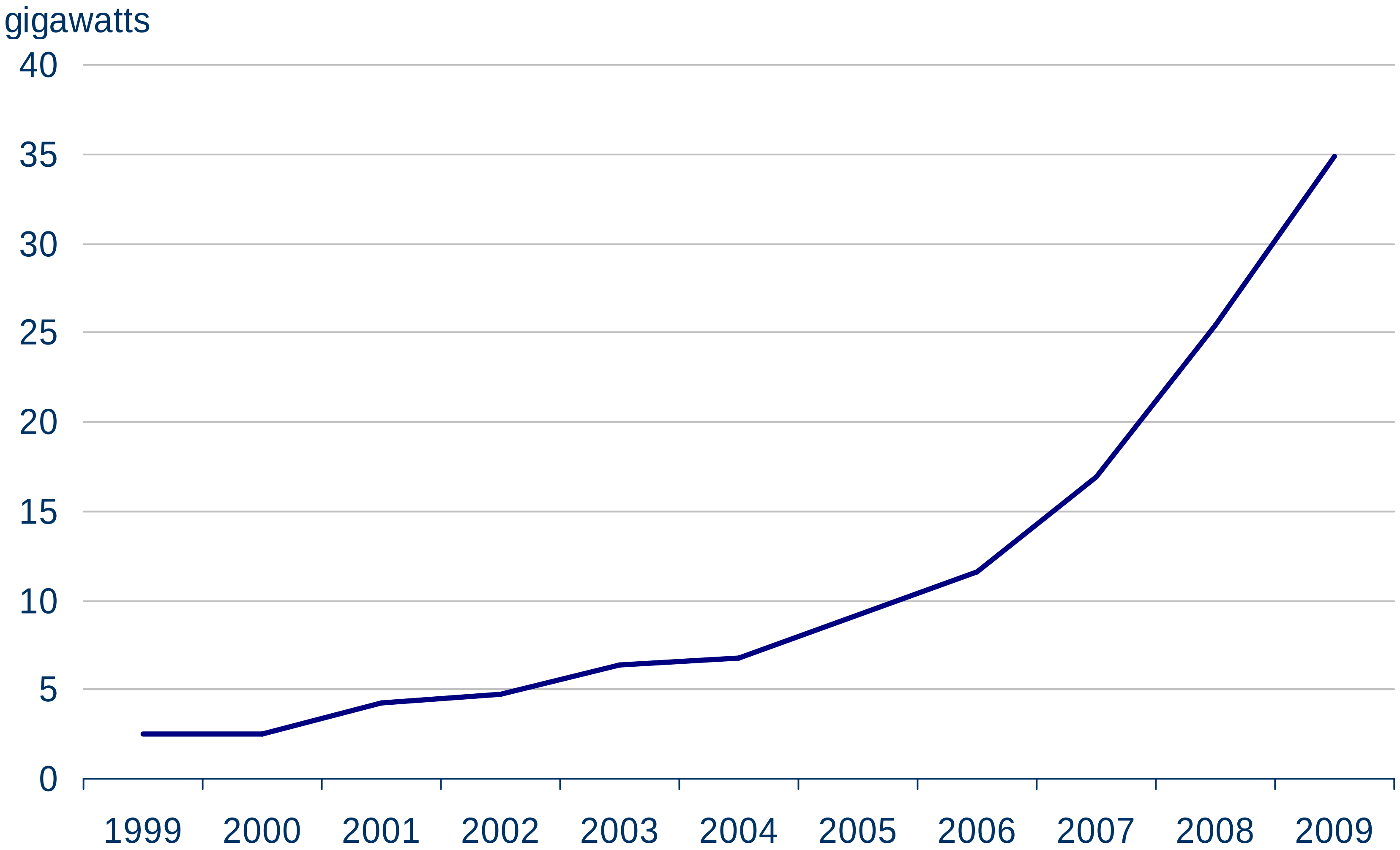
Modeling learning in the NEMS building modules

- Learning of conventional “mature” technologies (where shipments are a small fraction of cumulative sales) is exogenously specified by engineering/economic “menus” [1]
- CHP and distributed generation uses the same basic equation which is used for electricity capacity expansion [2]
- Costs for technologies designated as “infant” or “adolescent” decline from menu costs over time based on a logistic function specified by the curve’s inflection point, the ultimate price reduction, and the rate of price decline. [3]
- Potential enhancement to accelerate menu availability of advanced technologies when cumulative price changes exceeds thresholds [4]

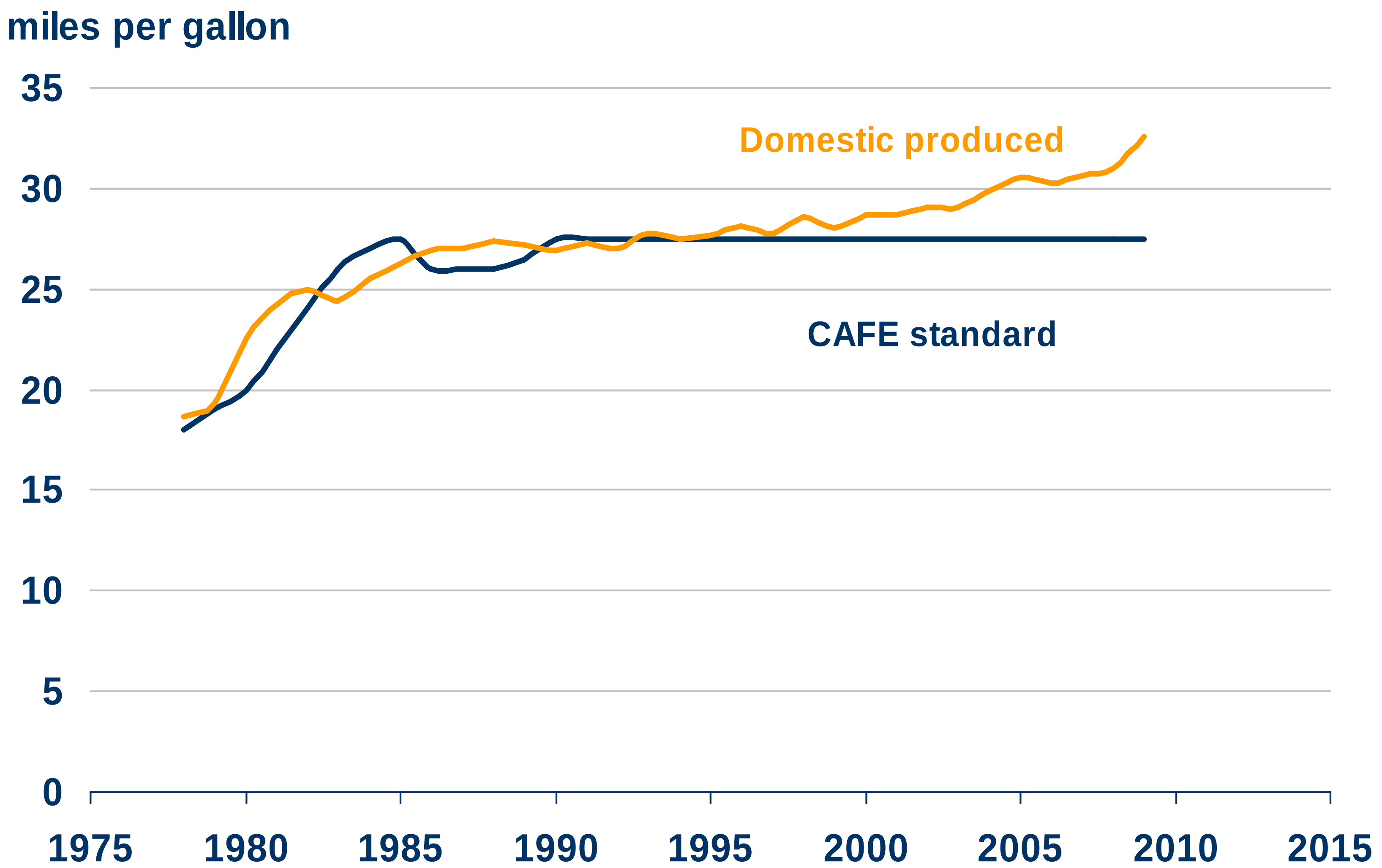
Technology learning features in the NEMS electricity module

- Capital costs and progress ratios reviewed regularly
- Autonomous minimum learning for international learning and R&D
- **Learning by Component**: Endogenously relate learning for common technologies
  - (e.g. capacity additions of advanced gas combined cycle results in component learning for IGCC, Adv Turbines and Advanced Biomass)

Installed wind capacity



CAFE standards for cars induced quick technology change in the 1970s and 1980s



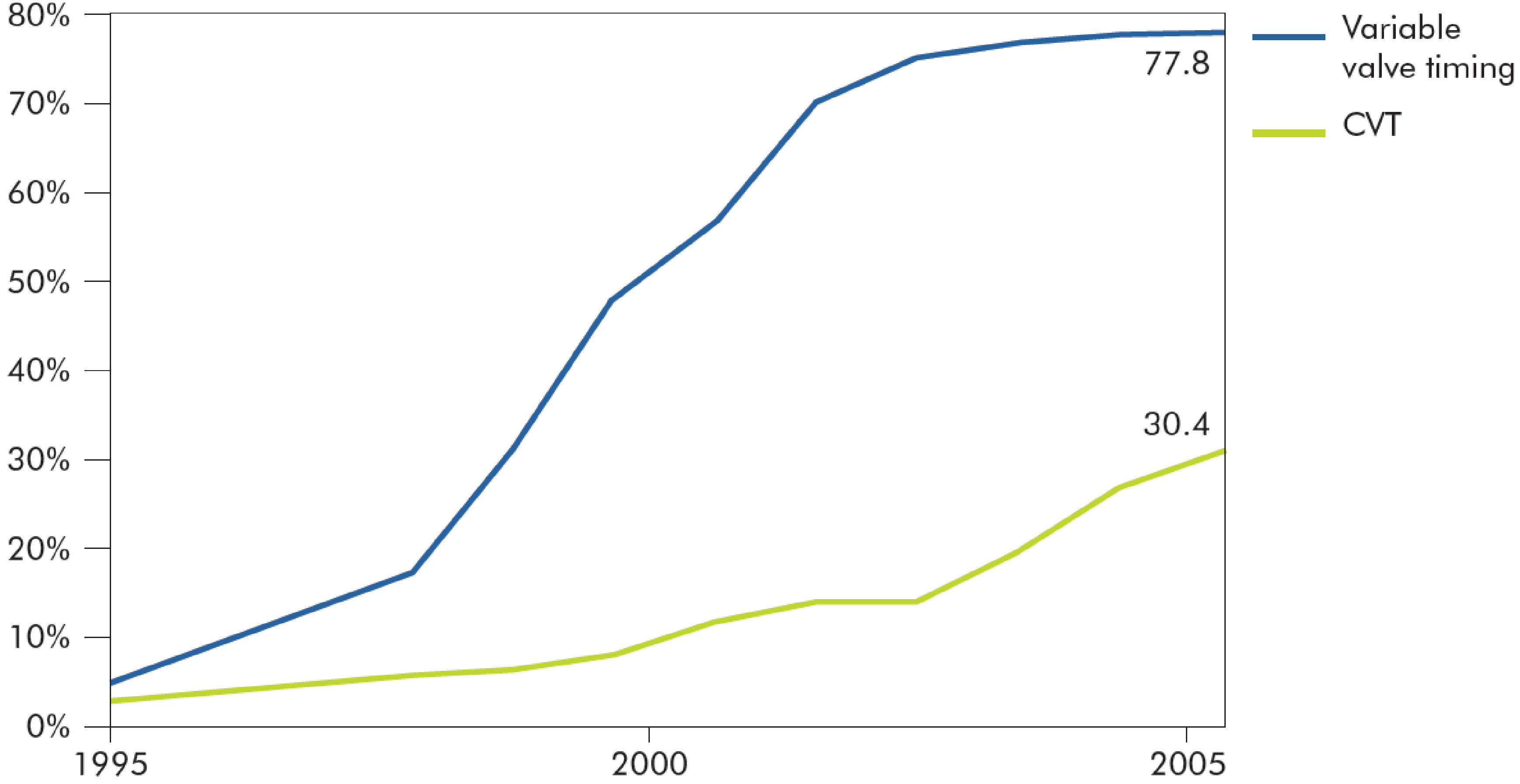
 Source: http://cta.ornl.gov/data/tedb28/Spreadsheets/Table4_20.xls

R&D program investments cannot be directly assessed using NEMS

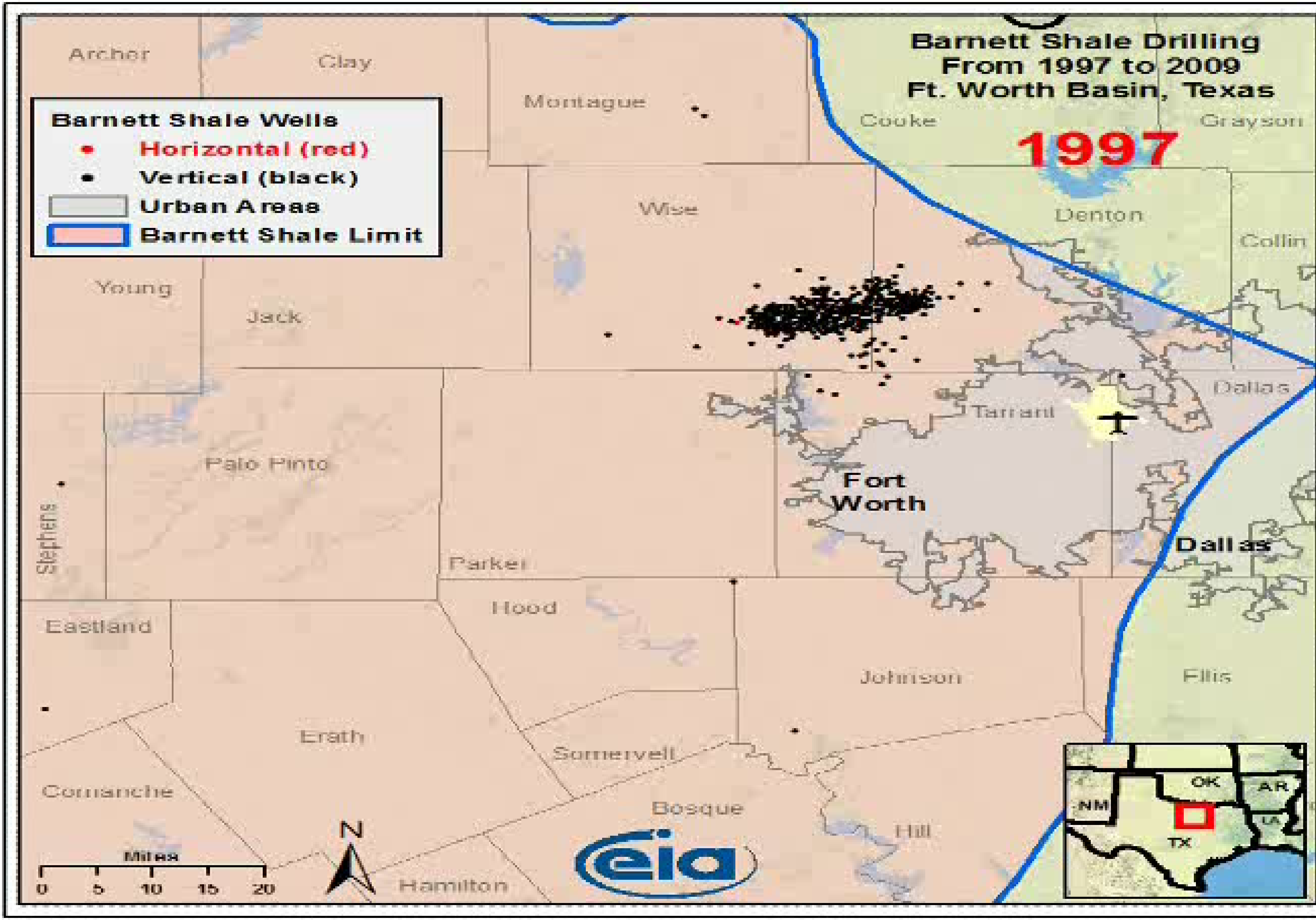
- Modeling the impact of R&D – the information challenge
- Timing and size of net change in federal R&D spending may differ (substantially) from authorized level
- There is no reliable relationship between the input of specific federal R&D spending and R&D outcomes
- Private R&D expenditures also matter – but we have little reliable data on technology-specific R&D expenditures in the U.S. or their results
- International private and public sector R&D investments are even less reliable than domestic ones
- Knowledge “spillover” (sharing) from international R&D is important and even less reliable and sparse

Variable valve timing and continuously variable transmission (CTV) in passenger LDVs in Japan

Market share in new vehicles



Source: JAMA 2008 & IEA 2009 *Transport, Energy and CO_2*.



Barnett Shale Drilling
From 1997 to 2009
Ft. Worth Basin, Texas
1997
Barnett Shale Wells
Horizontal (red)
Vertical (black)
Urban Areas
Barnett Shale Limit
Archer
Clay
Montague
Cooke
Grayson
Denton
Collin
Wise
Young
Jack
Palo Pinto
Tarrant
Dallas
Fort Worth
Dallas
Stephens
Parker
Hood
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Johnson
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Erath
Somervell
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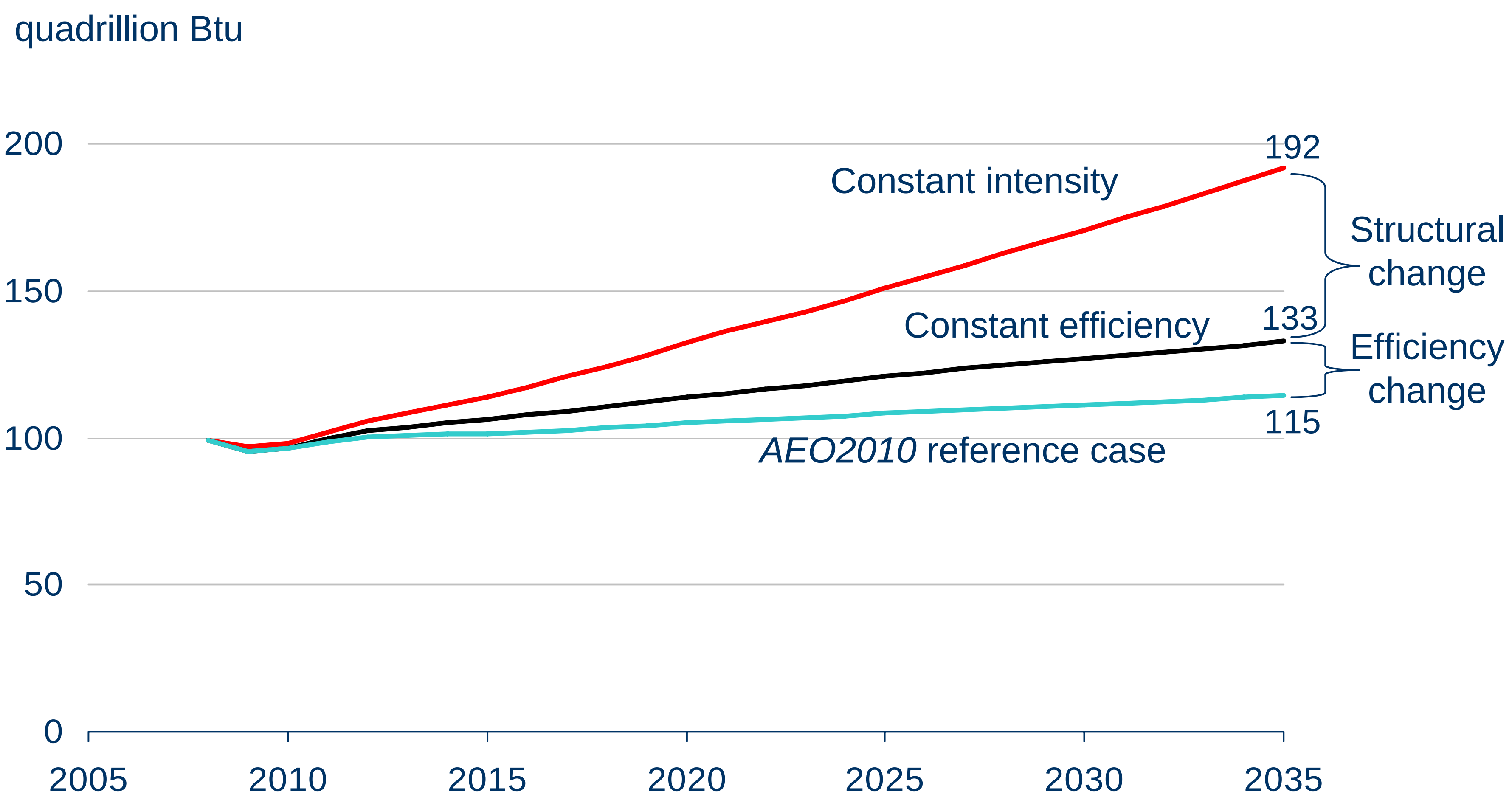
Energy efficiency gains reduce consumption 15% from where it would otherwise be; structural change is even larger



Access to shale gas has major implications for prices, production imports, and the Alaska gas pipeline

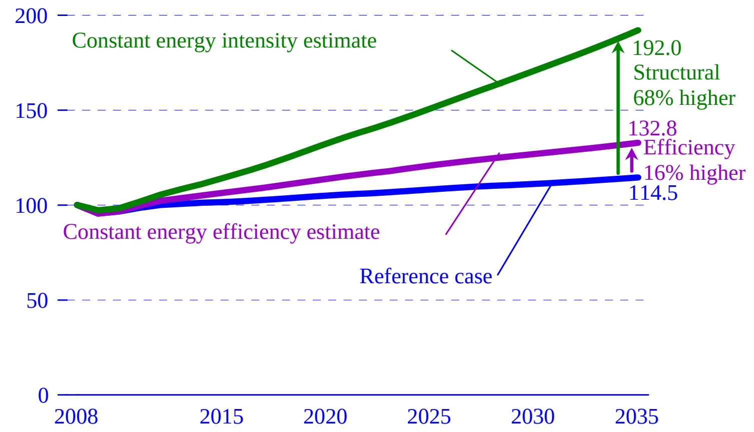
Table 7. Natural gas prices, supply, and consumption in four cases, 2035

Projection	Reference	No Shale Gas Drilling	No Low-Permeability Gas Drilling	High Shale Gas Resource
Henry Hub spot price (2008 dollars per million Btu)	8.88	10.37	10.88	7.62
Total U.S. natural gas production (trillion cubic feet)	23.3	19.1	17.4	25.9
Onshore Lower 48	17.1	12.5	10.4	20.0
Offshore Lower 48	4.3	4.7	5.1	4.0
Alaska	1.9	1.9	1.9	1.9
First year of operation for the Alaska natural gas pipeline	2023	2020	2020	2030
Total net U.S. imports of natural gas (trillion cubic feet)	1.5	3.7	4.5	0.8
Canada	1.7	2.5	2.7	1.4
Mexico	-1.0	-0.7	-0.5	-1.3
Liquefied natural gas	0.8	1.8	2.4	0.8
Total U.S. natural gas consumption (trillion cubic feet)	24.9	22.9	22.0	26.8
Electric power sector	7.4	6.1	5.5	8.7
Residential sector	4.9	4.8	4.7	5.0
Commercial sector	3.7	3.6	3.5	3.8
Industrial sector	6.7	6.5	6.4	7.0
Other	2.2	1.9	1.8	2.3

Structural change in the economy, is the main driver of projected reductions in energy intensity, but efficiency improvement also matters

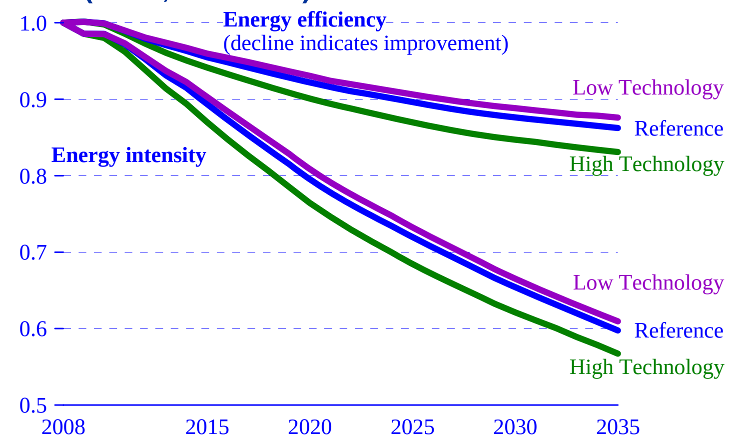
- •The constant energy intensity estimate assumes that the ratio of energy use to economic output remains fixed at its 2008 level.
- •The constant efficiency estimate similarly assumes that energy efficiency does not change from 2008.
- •Structure accounts for 76% of the 2035 difference between the Reference case constant energy intensity estimate.

Figure 19. Structural and efficiency effects on primary energy consumption in the AEO2010 Reference case (quadrillion Btu)

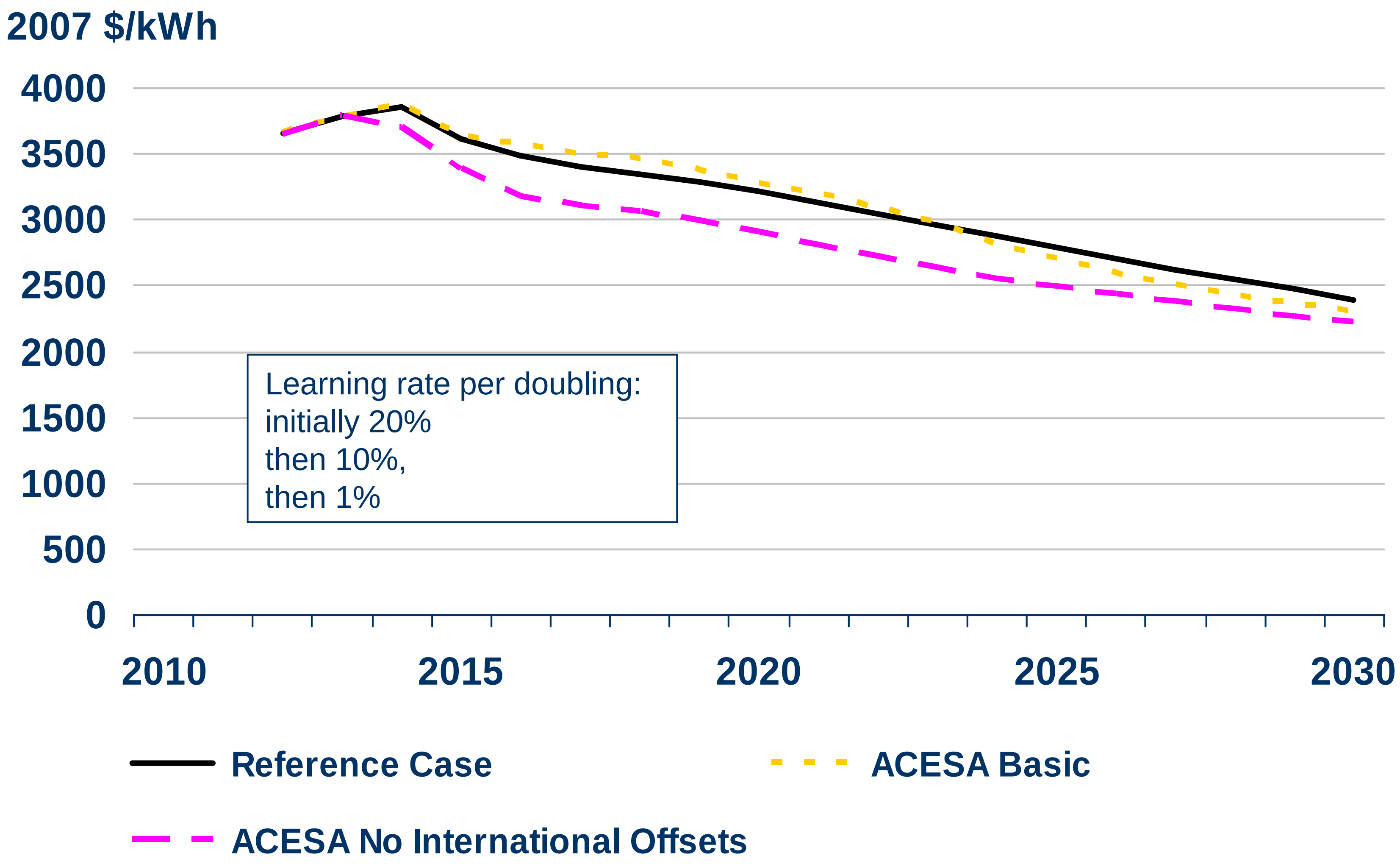


- •Low Technology case essentially freeze technologies to those available in 2009.
- •High technology has more efficient and less expensive equipment.
- •Dispersion across the cases for efficiency and intensity are similar – this reflects the fact that technology drives efficiency which is also part of intensity.

Figure 20. Energy efficiency and energy intensity in three cases, 2008-2035 (index, 2008 = 1.0)

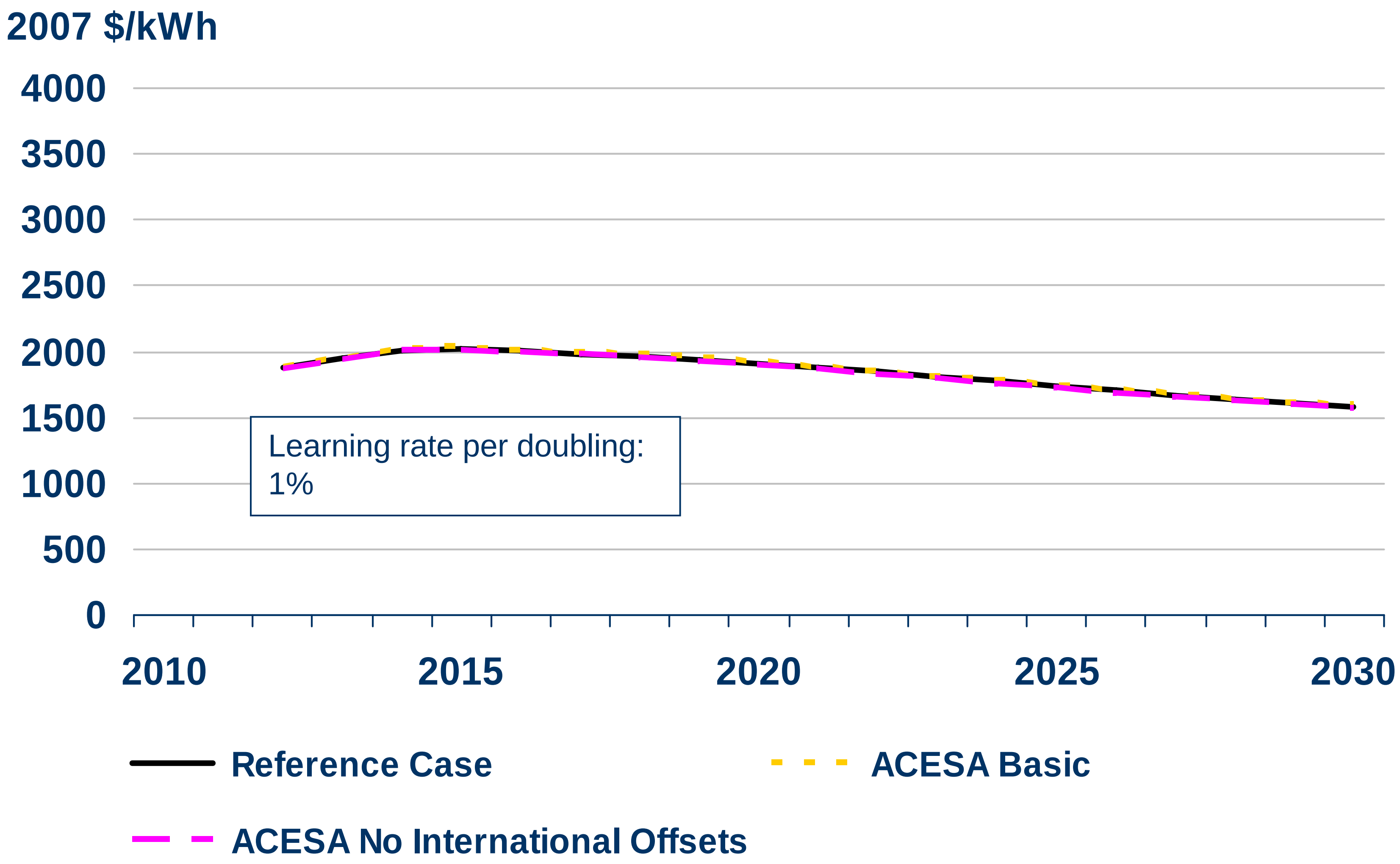


Overnight costs of new biomass IGCC plants



Source: EIA analysis of Waxman-Markey HR.2454

Little difference in overnight costs for new wind plants because most of the technology is very mature



Source: EIA analysis of Waxman-Markey HR.2454