

# Learning by Doing for Renewable Energy Technologies: Empirical Evidence from Iran

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# The concept of learning-by-doing (LBD)

- The idea was pioneered by Wright in his paper “*Factors Affecting the Cost of Airplanes*” in 1936.
- Later on, Arrow (a Noblist economist) originally modified the theory in his famous article “*The Economic Implications of Learning-by-doing*” in 1962.
- The major improvement in learning-by-doing was introduced by Alvarez and Amman “*Learning-by-doing under Uncertainty*” in 1999.
- Still the concept is in progress both technically and economically.

# Two main characteristics of LBD

- *Learning is the product of experience. Learning can take place through the attempt to solve a problem and therefore only takes place during activity.*
- *Learning associated with repetition of essentially the same problem is subject to sharply diminishing returns.*

# Learning curves

- Learning curve (Experience curve) is **quantitative counterpart** of LBD concept.
- It is an empirical relation stating that costs of a technology decreases **exponentially** as experience increases.
- The rationale is that as more development efforts are committed to a technology, **more opportunities for reducing costs and improving performance** will be found.
- The better the price/performance of a technology, the **more investment** will be attracted.

# Learning curves mathematics

- A simple mathematical formulation for the learning curve is :

$$C(E) = \frac{C_0}{\left(\frac{E}{E_0}\right)^\alpha} \qquad PR = \frac{1}{2^\alpha}$$

$C(E)$  = Investment cost of energy technology (\$/MW)

$E$  = Installed capacity of energy production (MW)

$C_0$  &  $E_0$  = starting points for the curve

$\alpha$  = Learning rate

PR= Progress ratio

# Learning curves mathematics (con't)

- *An 80% progress ratio ( $PR=0.8$ ) means that costs are reduced to 80% of the previous level for each doubling of cumulative experience.*

Figure 1. Estimated wind energy technologies progress ratios

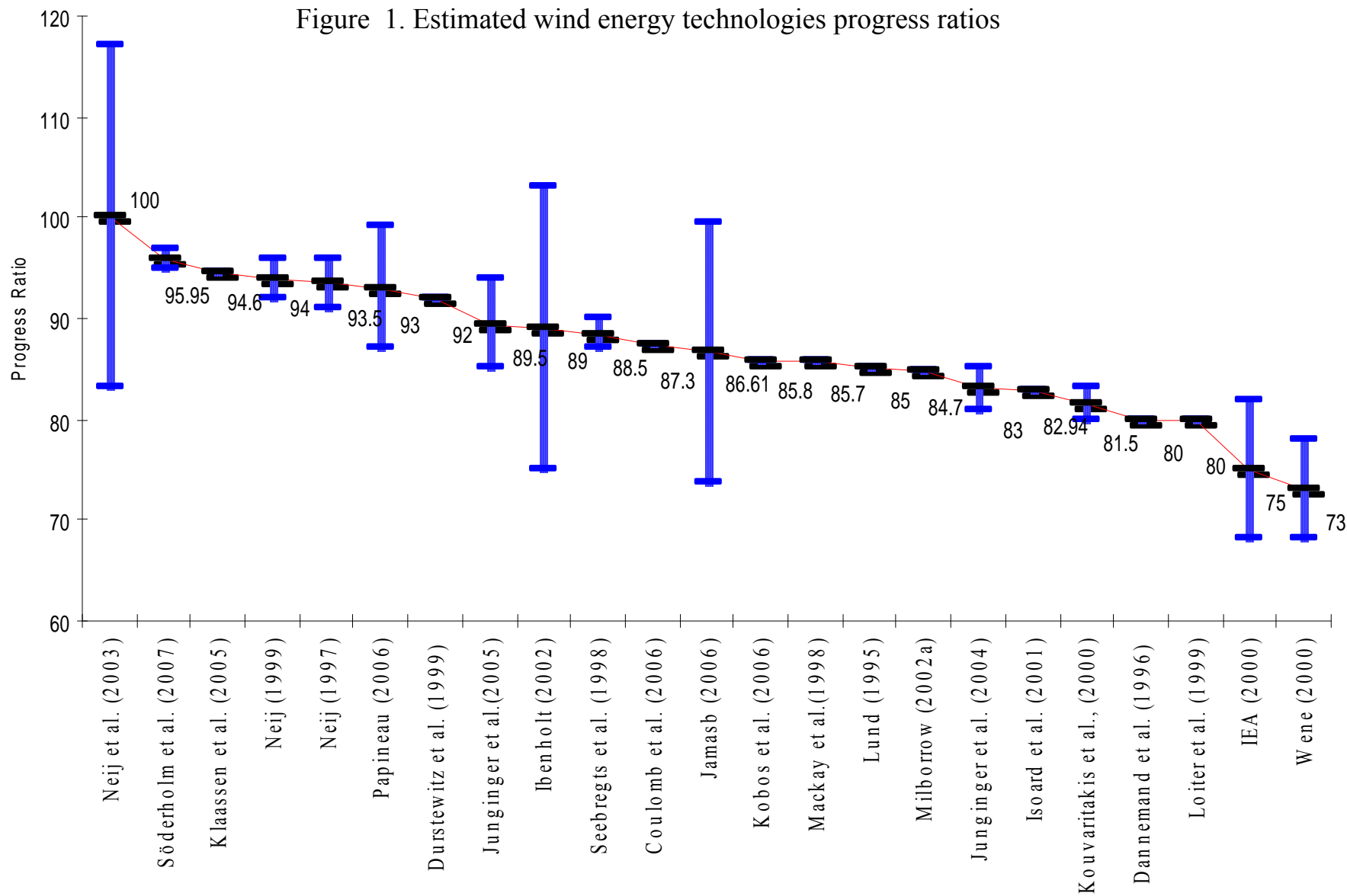
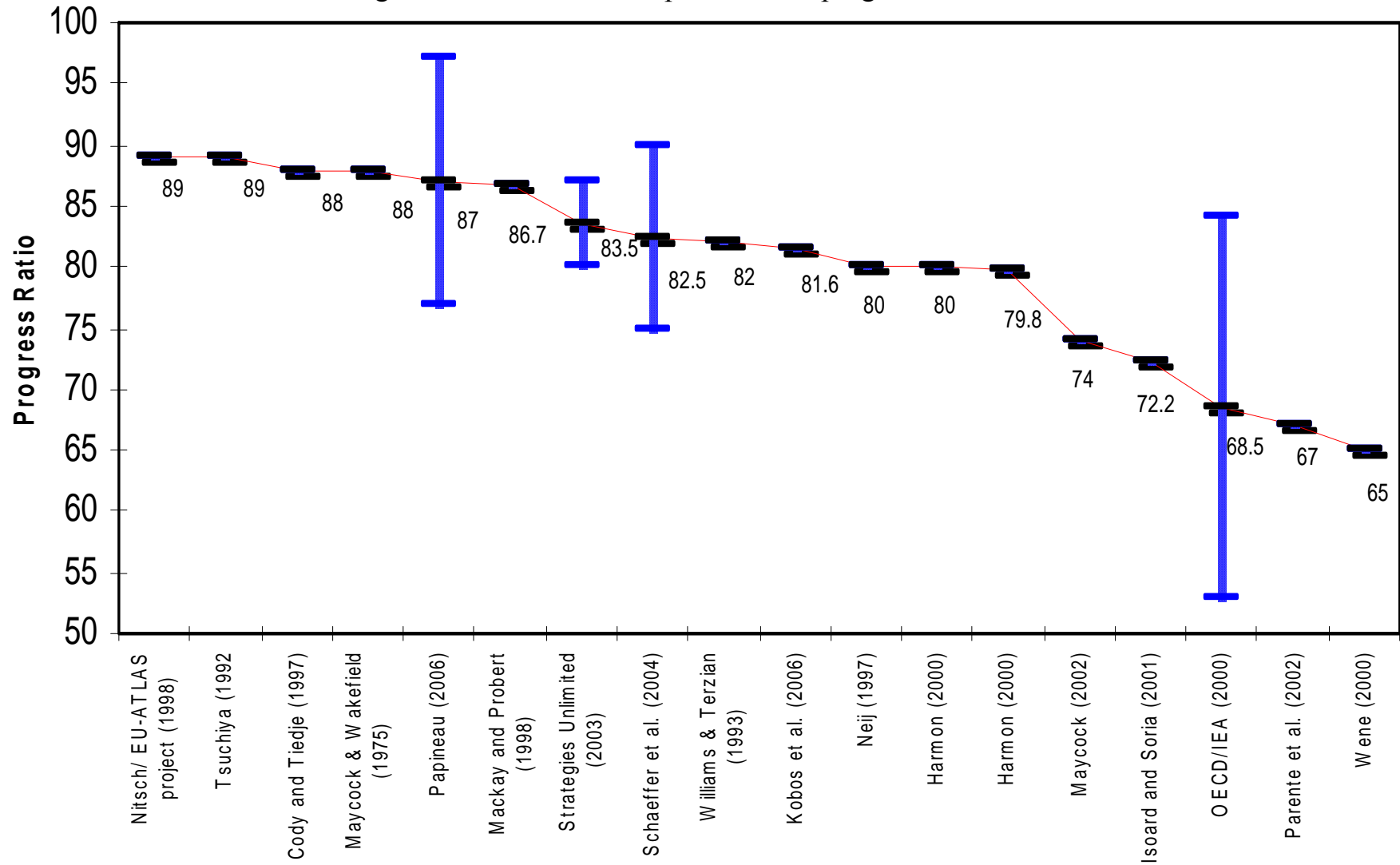


Figure 2. Estimated solar photovoltaic progress ratios



# Learning curve: Exogenous or Endogenous?

- The performance of a system will improve over time regardless of whether or not the system is employed.
- Exogenizing technology in energy models implies that, when the learning process is finished and technology has matured, **it can be employed without previous investment in the learning process.**
- The outcome of this externalization is **late adoption of new technologies.**

**The source of problem !**

# Learning curve: Exogenous or Endogenous?

- The main advantage of internalizing the process of technological learning, is inclusion of accumulated knowledge.
- In other words, embodiment of technical change can be considered as the root of investment dynamics.
- The usual approach is assuming **energy technology cost as a function of cumulative acquired knowledge** which reflects LBD.
- The parameters of an energy technology improve **as function of cumulative installed capacities**.

# Learning curve modeling

- The total cumulative cost ( $TC_{k'',t}$ ) is expressed as the integral of the specific cost curve:

$$TC_{k'',t} = \int_0^C SC_{k'',t}(C) \cdot dC = \int_0^C aC_{k'',t}^{-b} \cdot dC = \frac{a}{1-b} C_{k'',t}^{1-b}$$

$k''$  = Set of learning technologies

$C_{k'',t}$  = Non-decreasing variable

$$C_{k'',t} = C_{k'',o} + \sum_{\tau=1}^t INV_{k'',\tau}$$

# Learning curve modeling (con't)

- The objective function comprises the usual computation of all the costs for the other non-learning technologies ( $k'$ ), plus the discounted investment costs for the learning technologies ( $k''$ ):

$$Z = \sum_{t=1}^{\pi} (1+d)^{1-t} \cdot ANC(k', d, p, f)_t \cdot (1+(1+d)^{-1} + (1+d)^{-2} + \dots + (1+d)^{1-\tau}) + \sum_{k''} \sum_t d \cdot IC_{k'', t}$$

# Learning curve modeling (con't)

$Z$  = The net present value of the total cost of the electricity system

$d$  = The general discount rate

$\tau$  = The number of periods in the planning horizon

$\pi$  = The number of years in each period  $t$

$ANC( , d, p, f)_t$  = The annual cost for period  $t$ , which is the sum over all (non learning) technologies , all demand segments  $d$ , all pollutants  $p$ , and all input fuels  $f$  of the various costs incurred

$TC_{k,t}$  = The investment cost associated with a given learning technology in the period  $t$ .

# Learning curve modeling (con't)

- In order to specify the learning curve to be interpolated, a maximum capacity must be defined ( $C_{k'', \max}$ ).
- This implies an upper bound for the capacity of the technology and will affect the segmentation.
- The corresponding maximum cumulative cost is given by:

$$TC_{k'', \max} = \frac{a}{1-b} (C_{k'', \max})^{1-b}$$

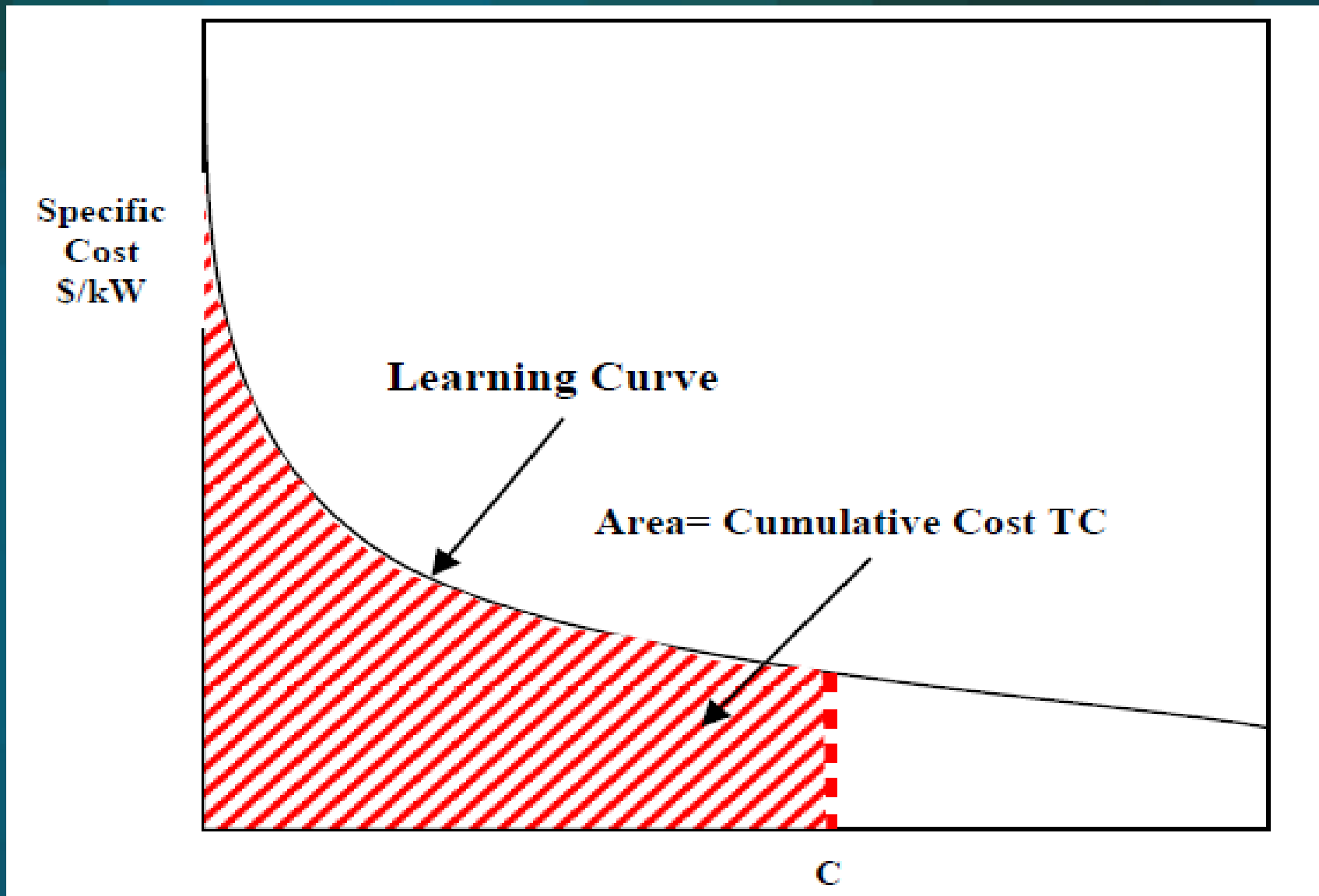
# Learning curve modeling (con't)

- Besides the maximum cumulative cost, the number of segments  $N$  for the cumulative cost curve and the corresponding cumulative capacities must also be specified, respectively:

$$TC_{i,k} = TC_{0,k} + \frac{1}{\sum_{i=0}^{N-1} \frac{1}{2^{N-i}}} (TC_{k,\max} - TC_{0,k})$$

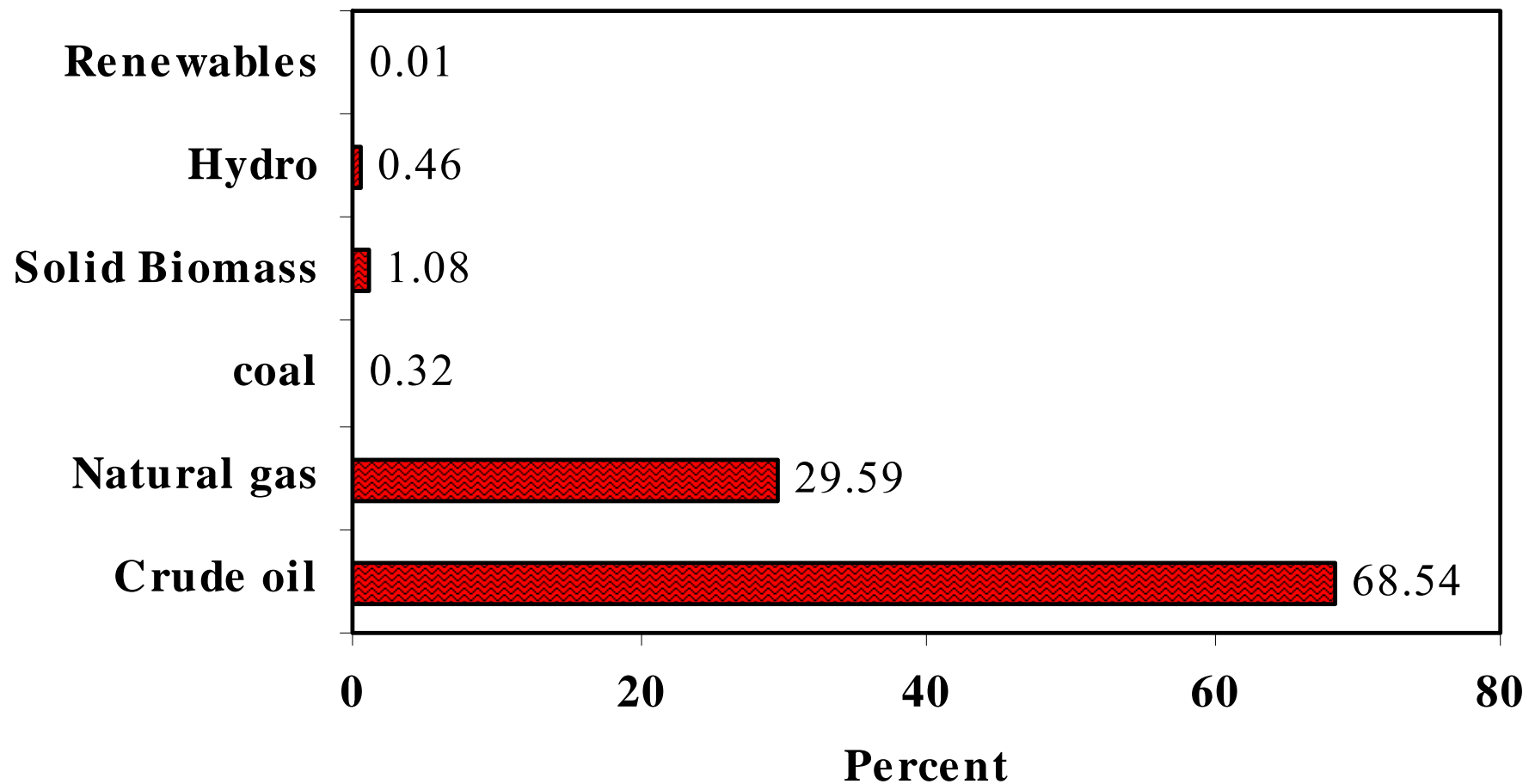
$$C_{i,k} = \left( \frac{(1-b)}{a} (TC_{i,k}) \right)^{\frac{1}{1-b}}$$

Figure 3. Cumulative cost curve as the area below the learning Curve



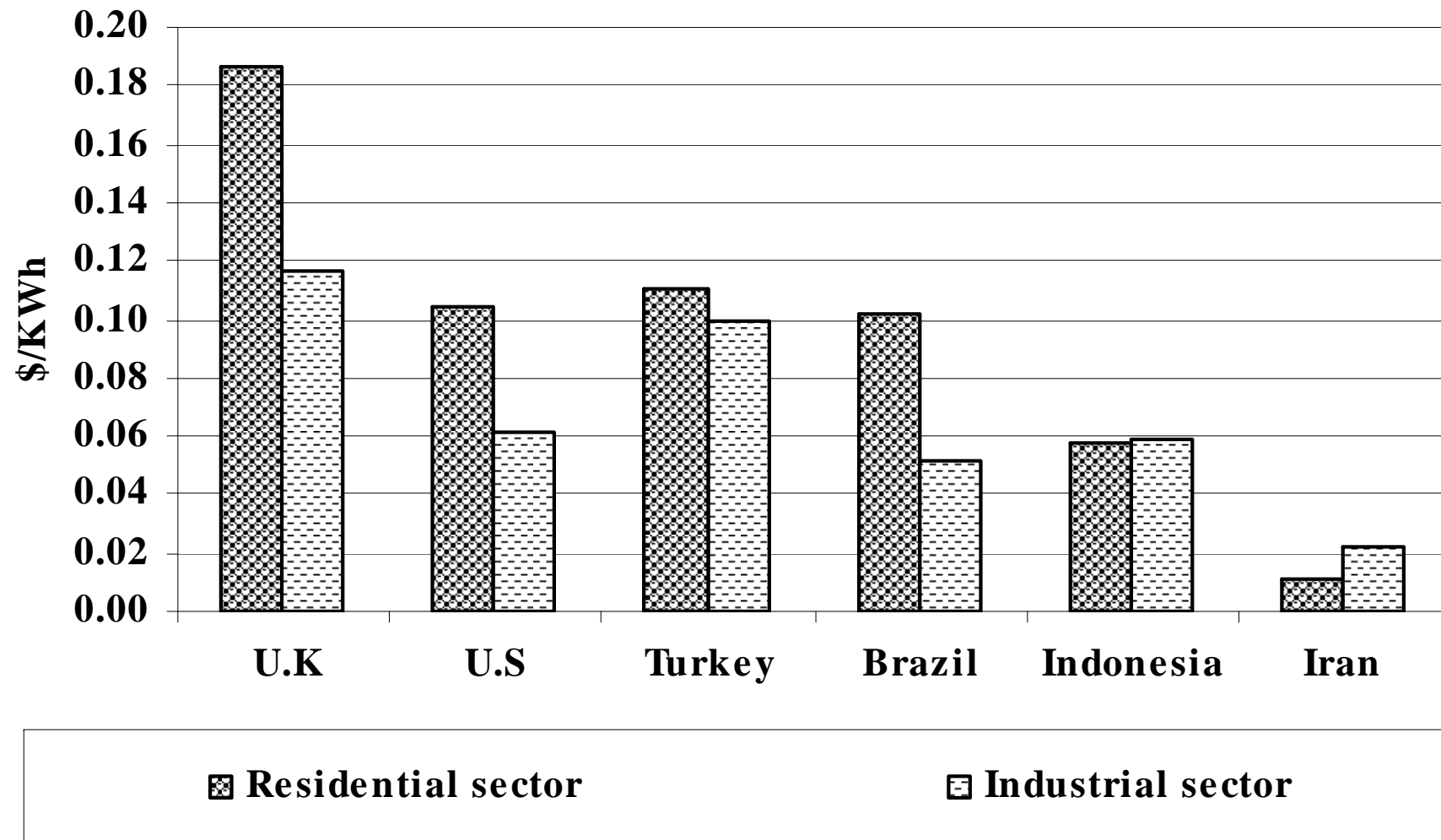
# Main characteristics of the Iranian electricity sector

Figure 4. The dominant share of fossil fuels as energy carriers in final energy consumption



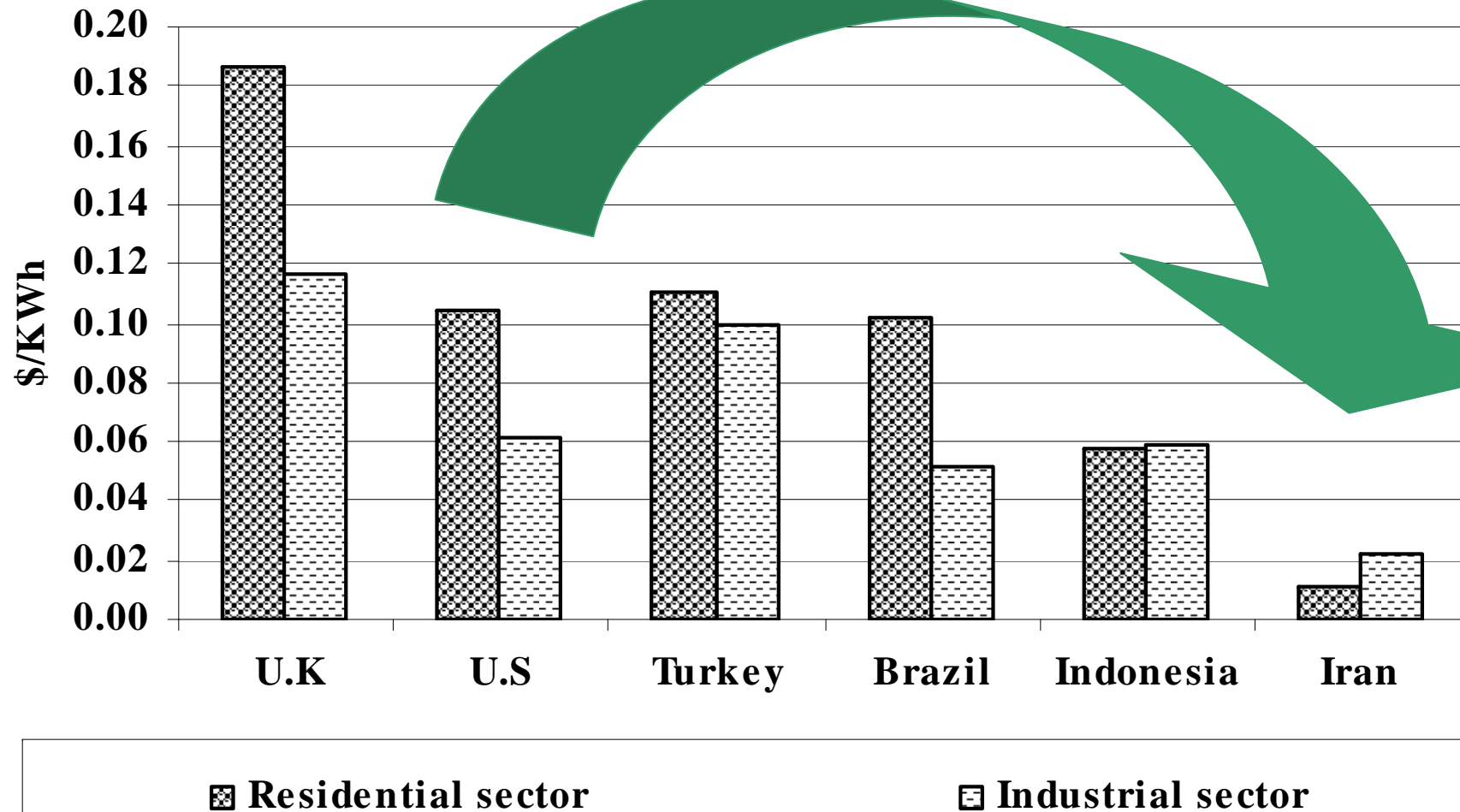
# Main characteristics of the Iranian electricity sector

Figure 5. Energy subsidization and price distortions



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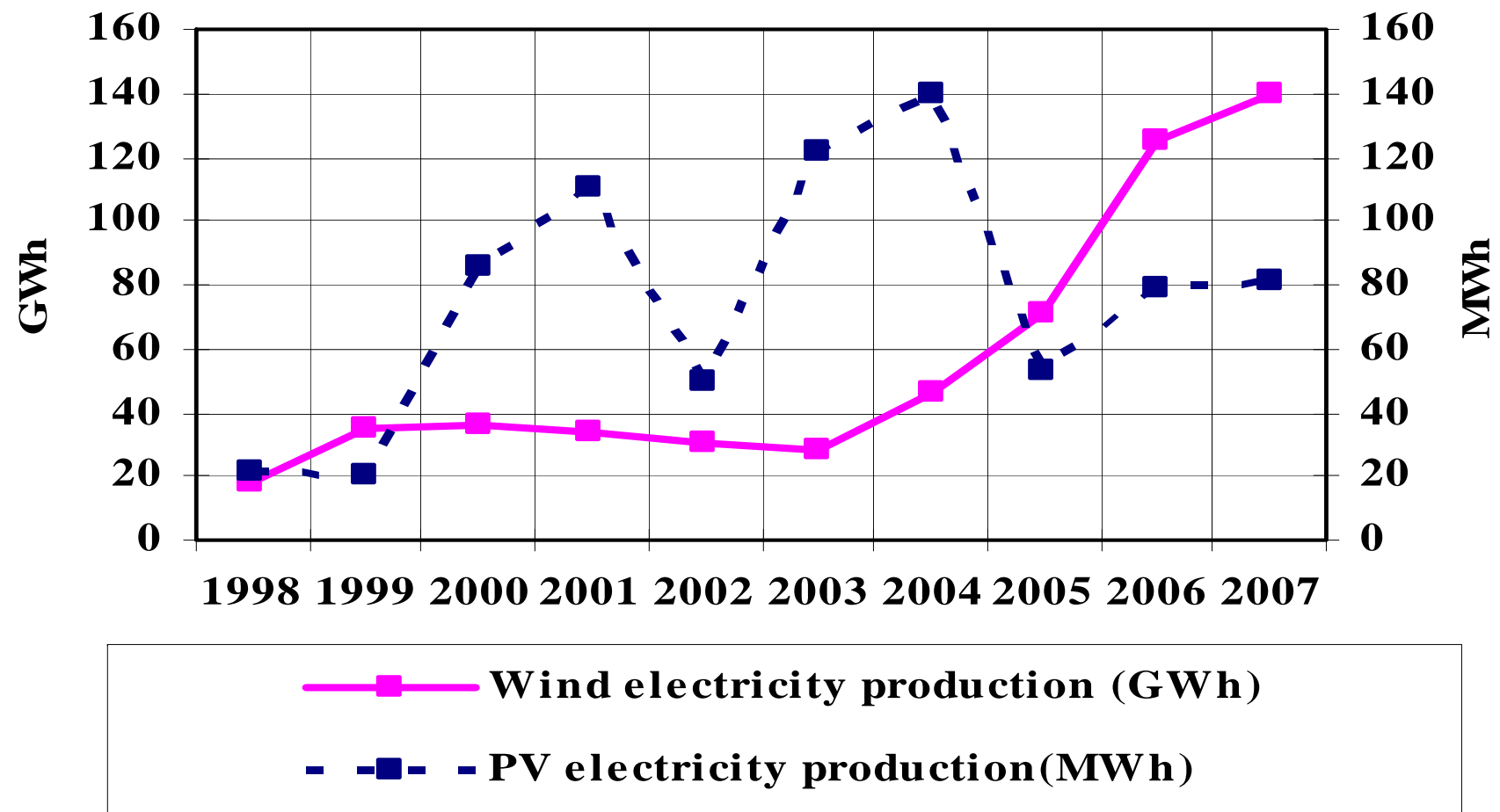


# Main characteristics of the Iranian electricity sector

Power Plant	CO <sub>2</sub> emission Million tones	Share in total power sector CO <sub>2</sub> emission
Steam	58.11	52.67
Gas Turbine	32.25	29.23
Combined Cycle	19.68	17.84
Diesel	0.17	0.16

# Main characteristics of the Iranian electricity sector

Figure 6. Total wind and PV power production during 1998-2007

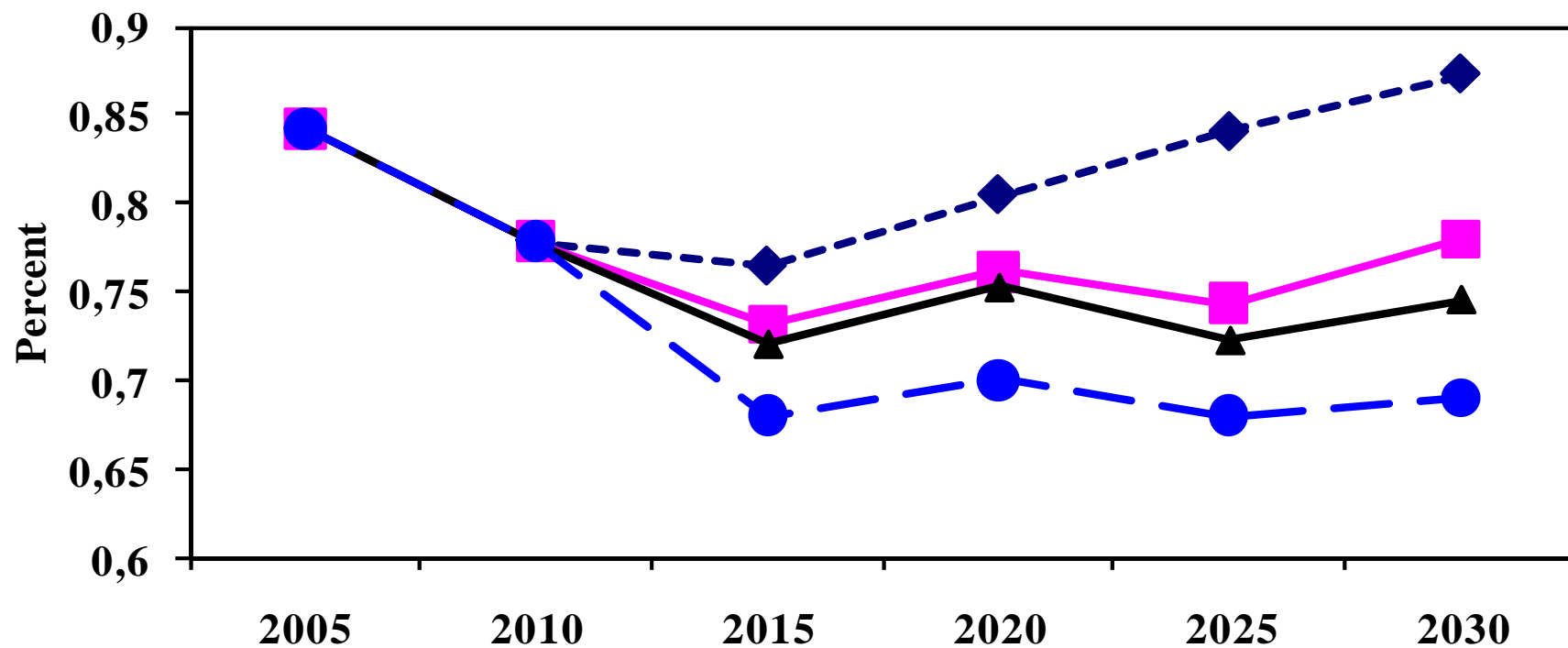


# Case study

- The optimization model was performed under 24 different scenarios.
- The business-as-usual (BaU) scenario was characterized by:
  - All energy technologies have non-learning processes
  - No environmental taxation
  - Energy pricing distortions
- All other scenarios were divided into learning and non-learning processes.
- The progress ratios for Wind and Solar technologies were assumed 73% and 65%, respectively.

Scenario	Learning Technology	Progress Ratio %	CO <sub>2</sub> Emission taxation	Subsidy Removal
B1 (BAU)	--	--	-	-
B2	--	--	+	-
B3	--	--	-	+
B4	--	--	+	+
W1	Wind	86	-	+
W2	Wind	86	+	+
W3	Wind	86	-	-
W4	Wind	86	+	-
W5	Wind	73	-	+
W6	Wind	73	+	+
W7	Wind	73	-	-
W8	Wind	73	+	-
P1	PV	80	-	+
P2	PV	80	+	+
P3	PV	80	-	-
P4	PV	80	+	-
P5	PV	65	-	+
P6	PV	65	+	+
P7	PV	65	-	-
P8	PV	65	+	-
WP1	Wind & PV	Wind(86) & PV(80)	-	+
WP2	Wind & PV	Wind(86) & PV(80)	+	+
WP3	Wind & PV	Wind(86) & PV(80)	-	-
WP4	Wind & PV	Wind(86) & PV(80)	+	-

Figure 7. The share of thermal power plants under different non-learning scenarios



---◆--- B1(BAU)

—■— B2

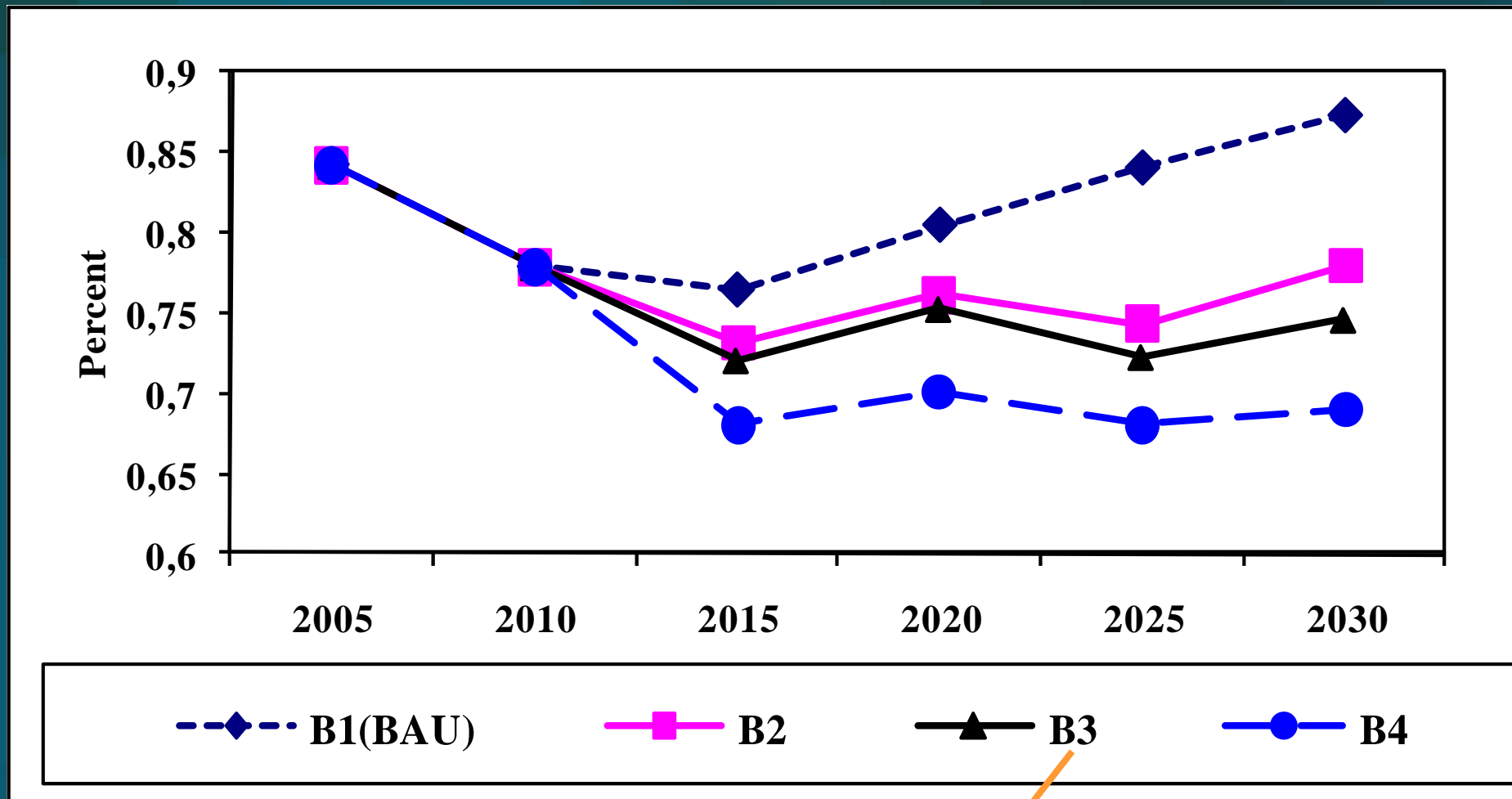
—▲— B3

—●— B4

Emission taxation

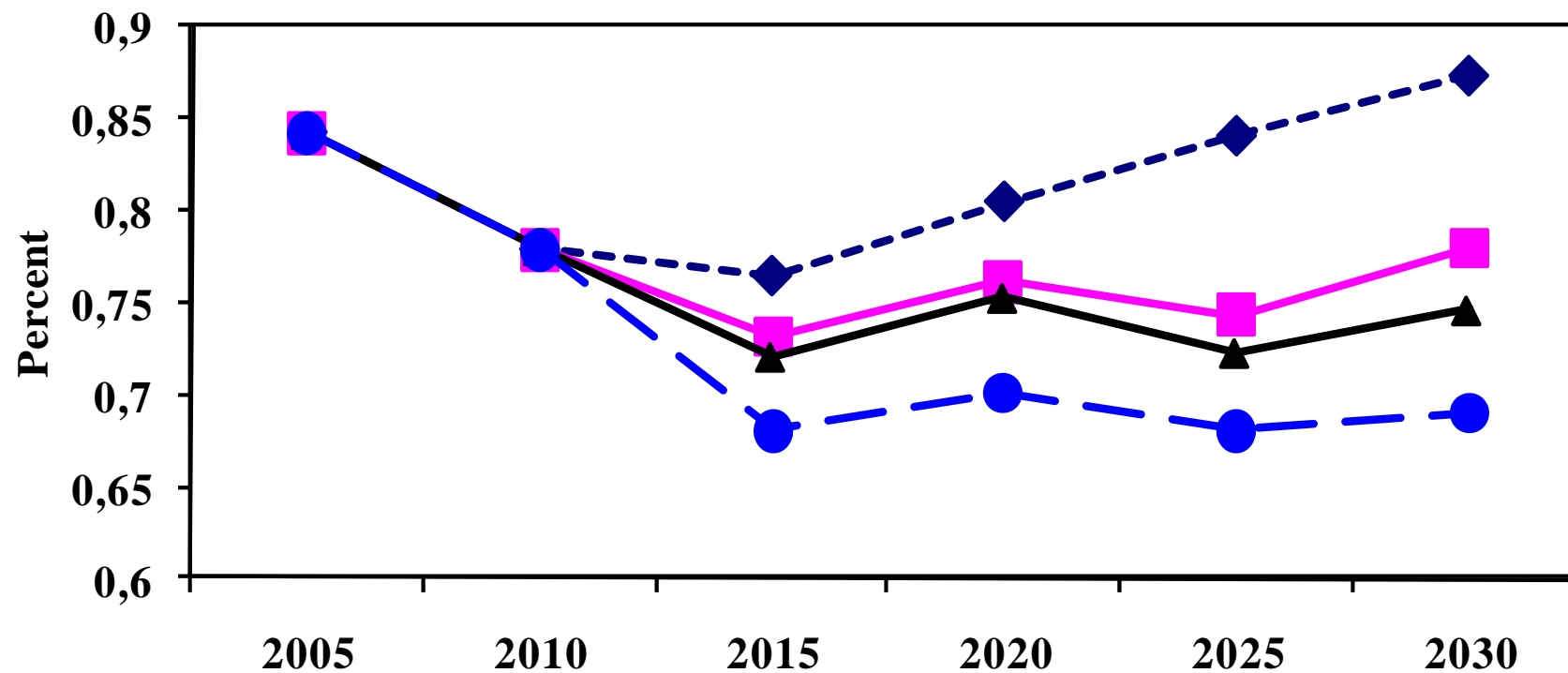
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Figure 7. The share of thermal power plants under different non-learning scenarios



Subsidy phase-out

Figure 7. The share of thermal power plants under different non-learning scenarios



---◆--- B1(BAU)

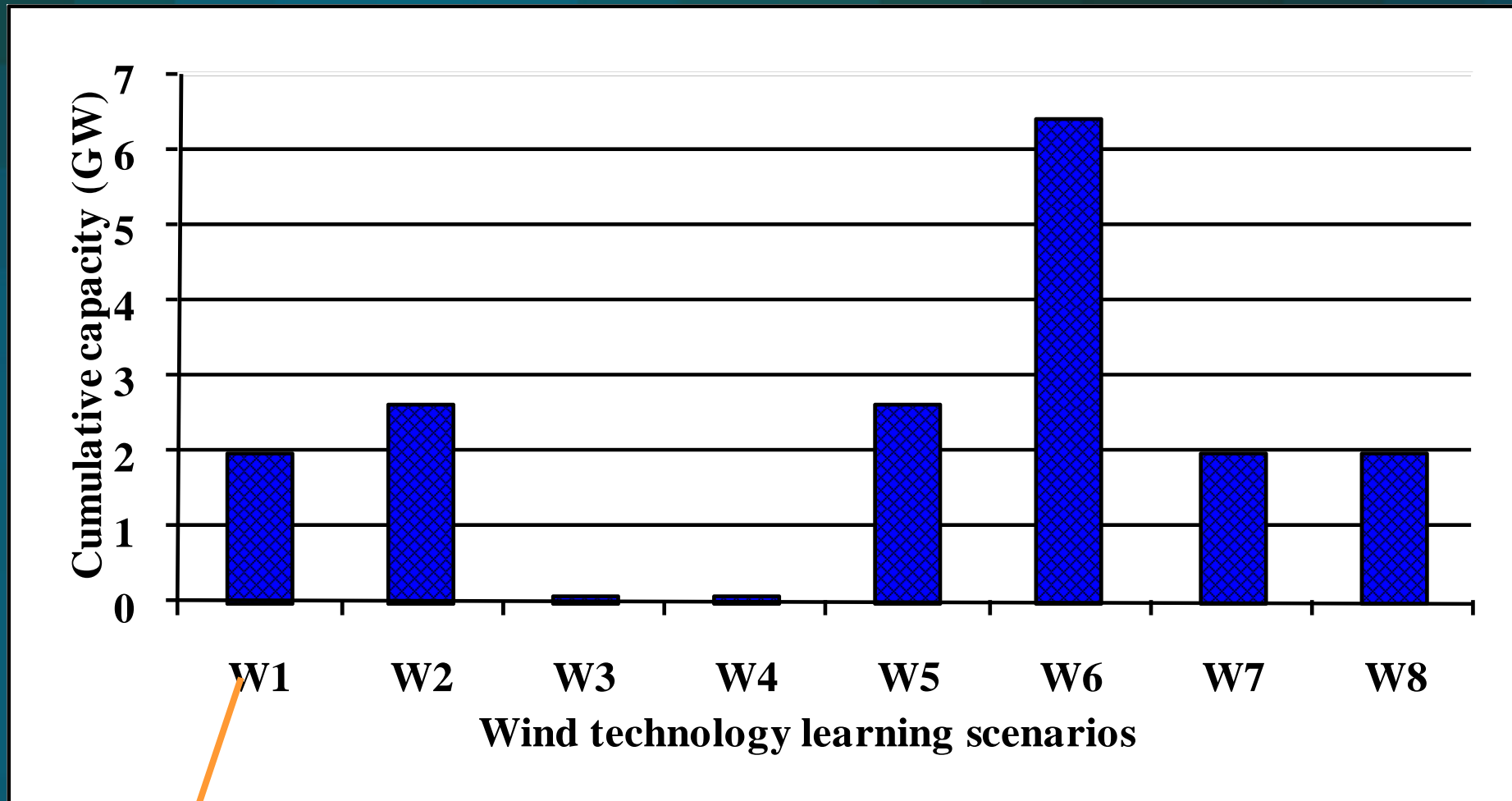
—■— B2

—▲— B3

—●— B4

Emission taxation + Subsidy phase-out

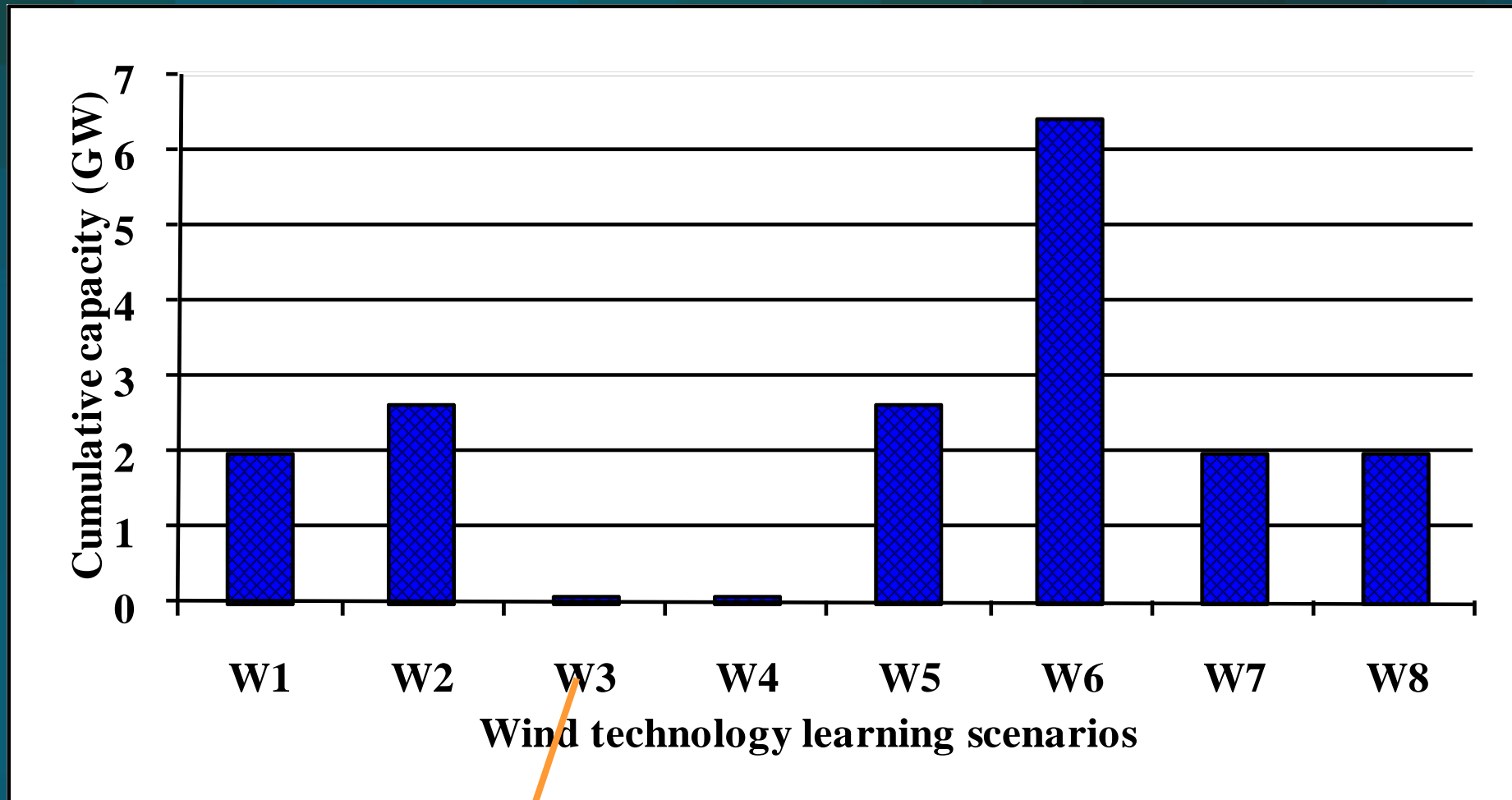
Figure 8. The effect of learning by doing on the wind energy technology installed capacity



No emission taxation + Subsidy phase-out

(PR=86%)

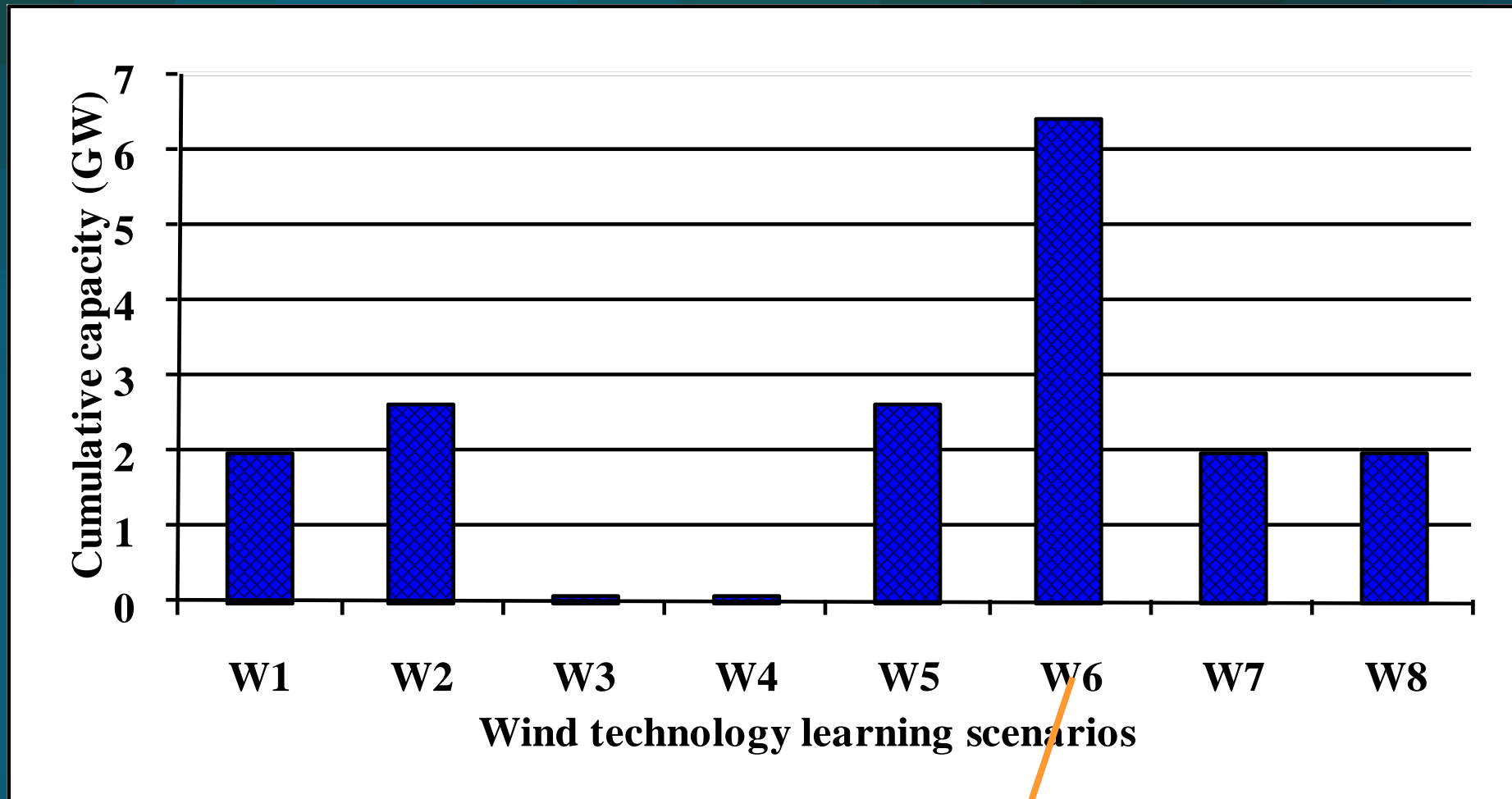
Figure 8. The effect of learning by doing on the wind energy technology installed capacity



No emission taxation + Energy subsidization

(PR=86%)

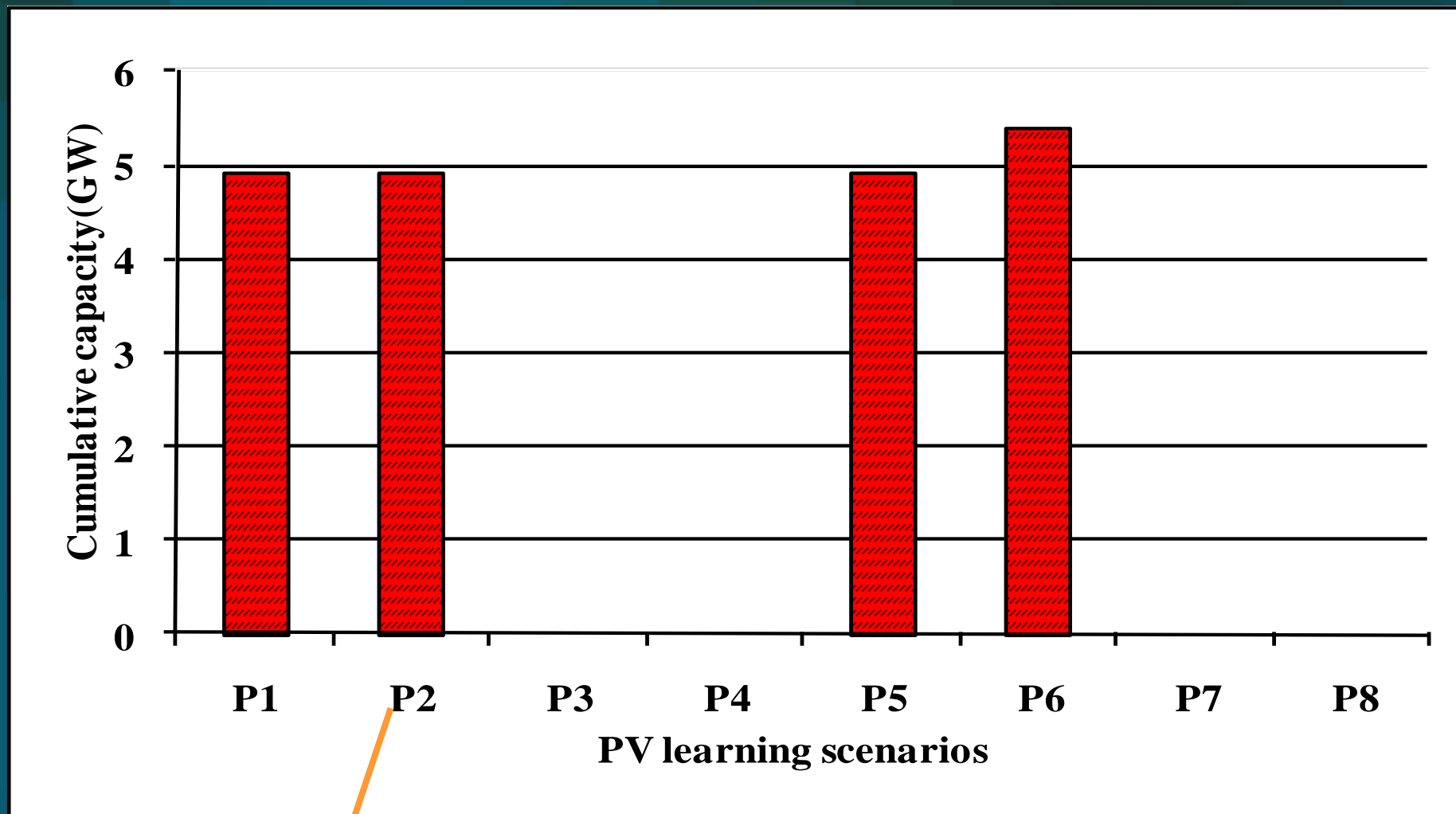
Figure 8. The effect of learning by doing on the wind energy technology installed capacity



Emission taxation + Subsidy phase-out

(PR=73%)

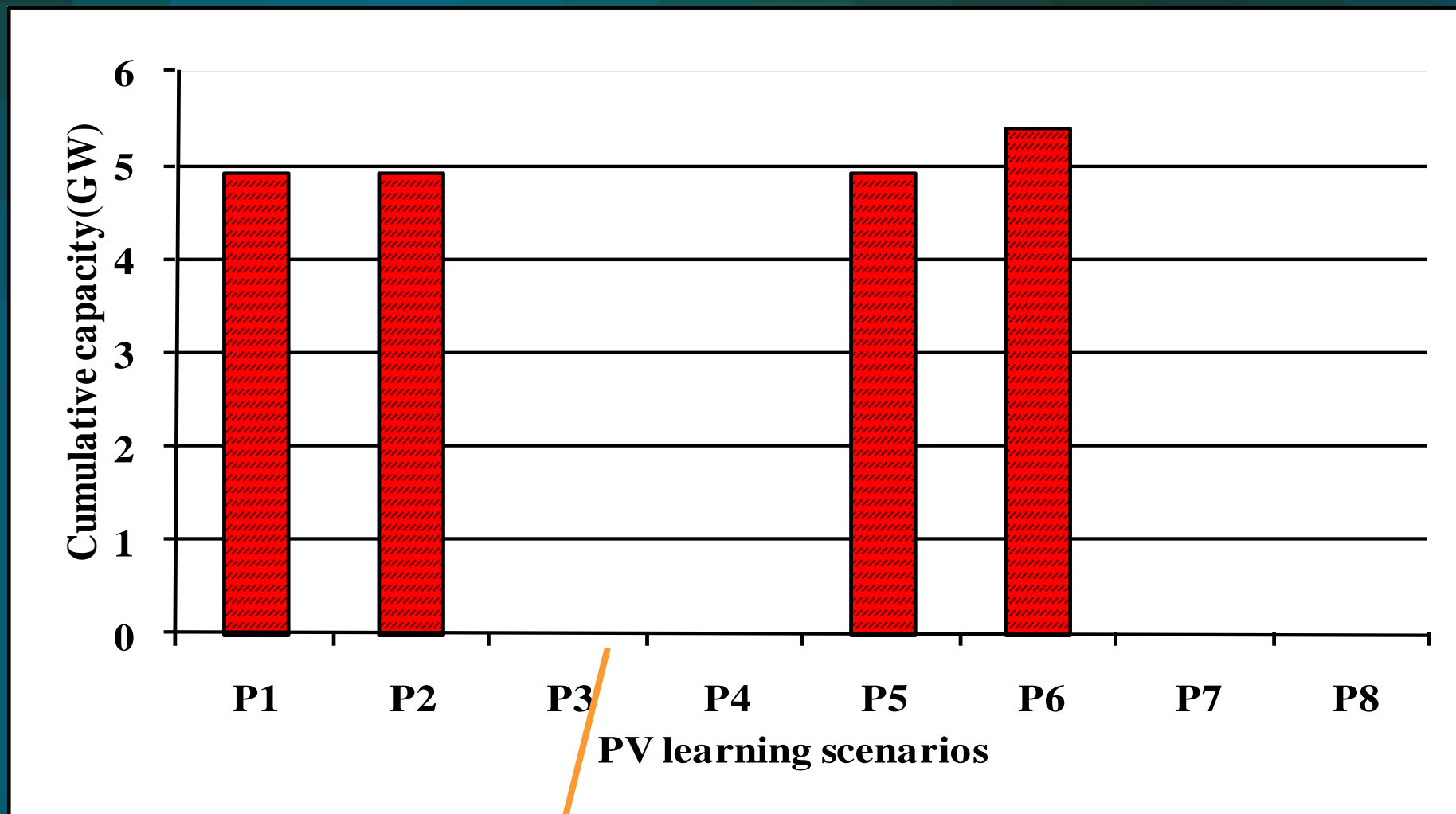
Figure 9. The effect of learning by doing on PV technology installed capacity



Emission taxation + Subsidy phase-out

(PR=80%)

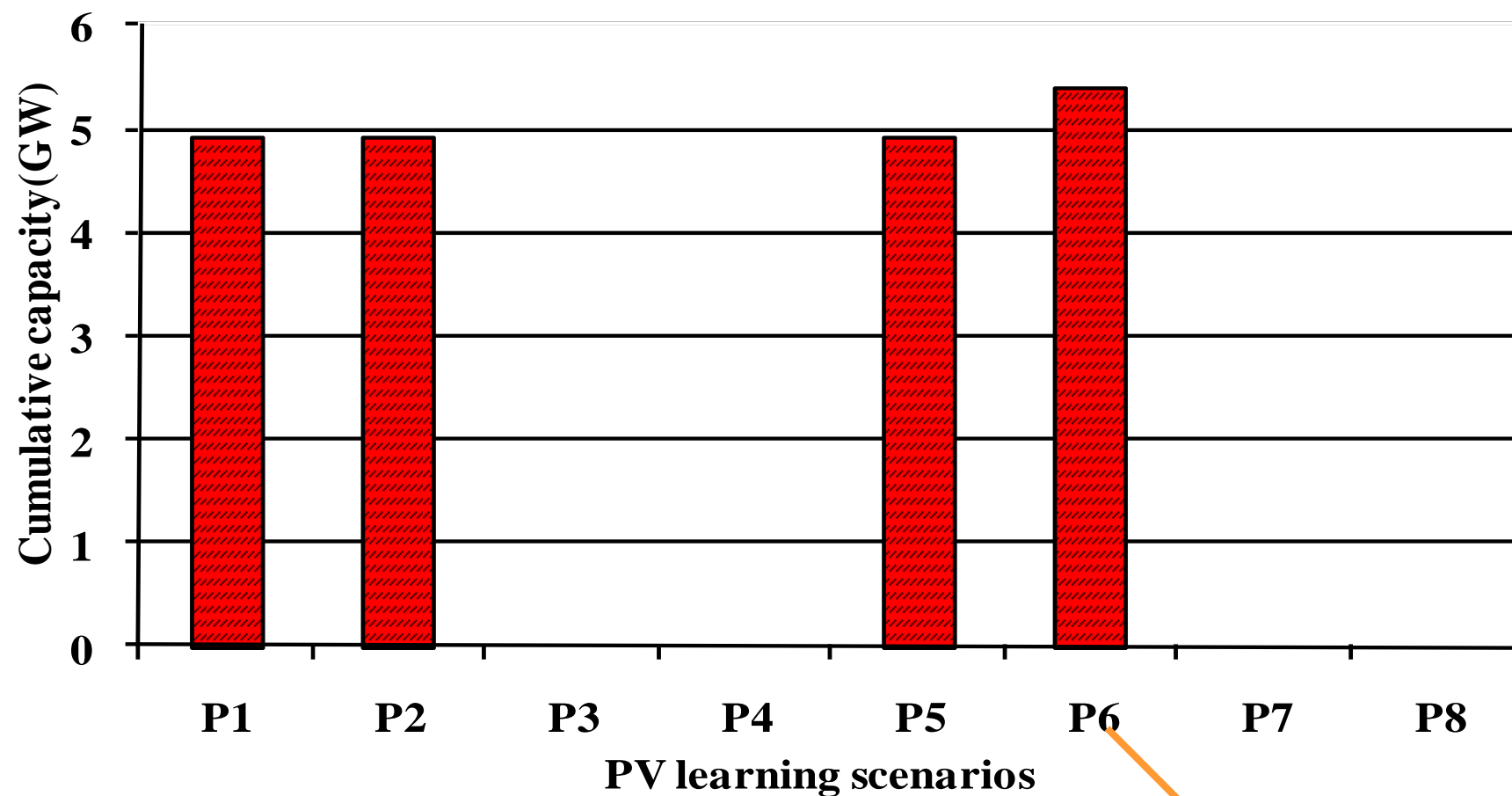
Figure 9. The effect of learning by doing on PV technology installed capacity



No emission taxation + Energy subsidization

(PR=80%)

Figure 9. The effect of learning by doing on PV technology installed capacity



Emission taxation + Subsidy phase-out  
(PR=65%)

Figure 10. Share of different technologies in total RE installed capacity under joint learning scenario

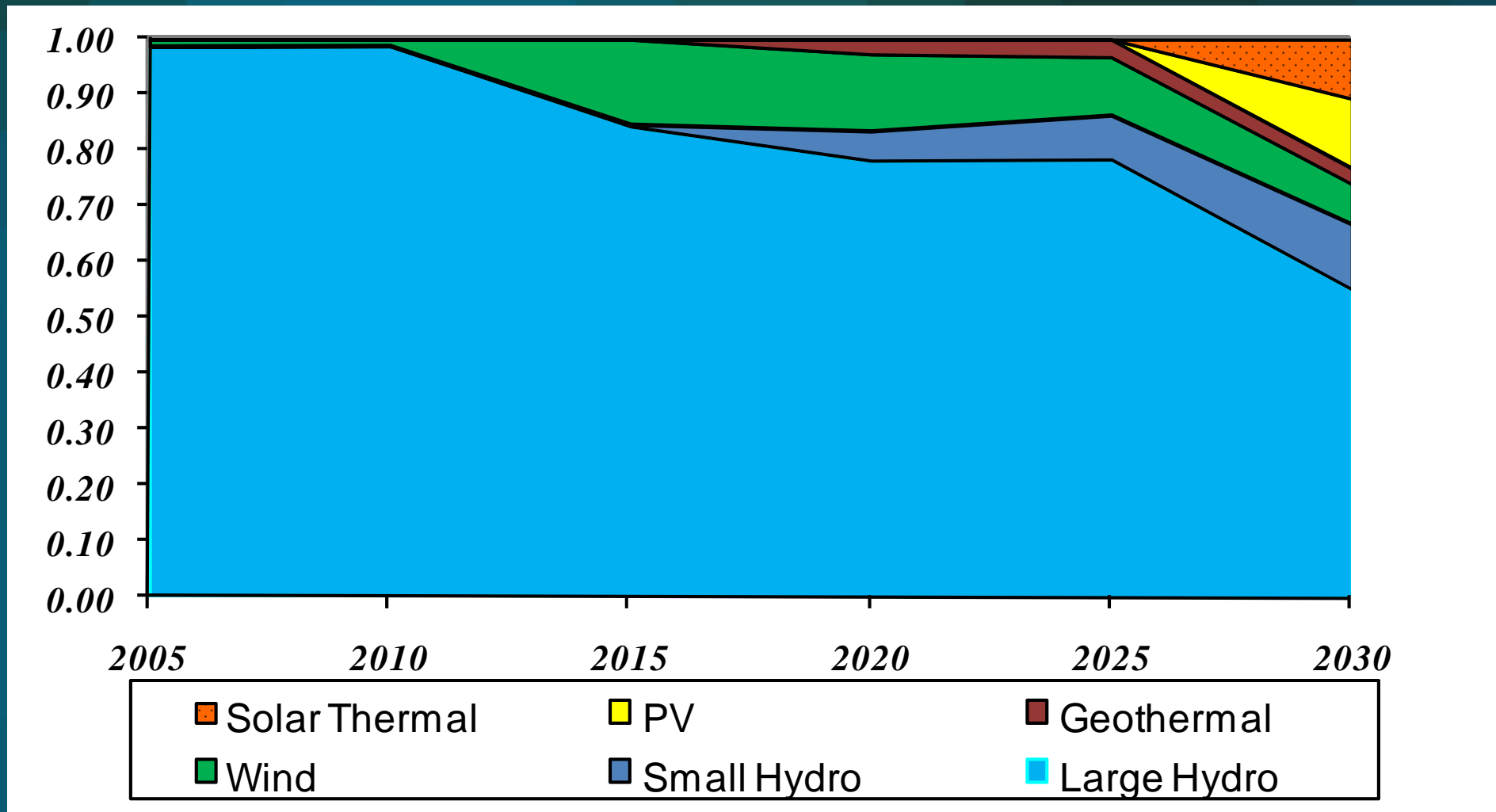


Figure 11. Power sector accumulated CO<sub>2</sub> emission under non-learning scenarios

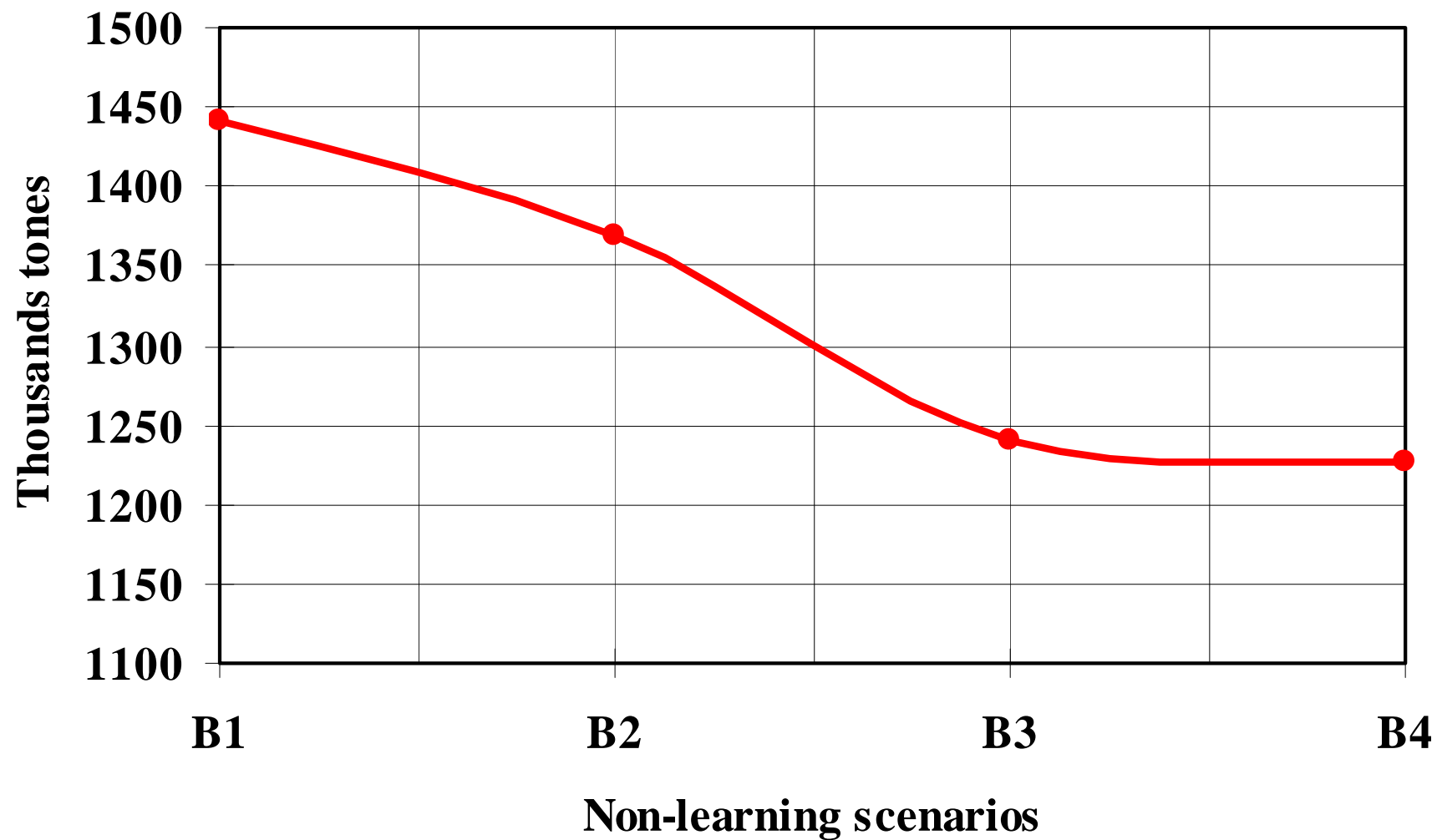


Figure 12. Power sector accumulated CO<sub>2</sub> emission under wind technology learning scenarios

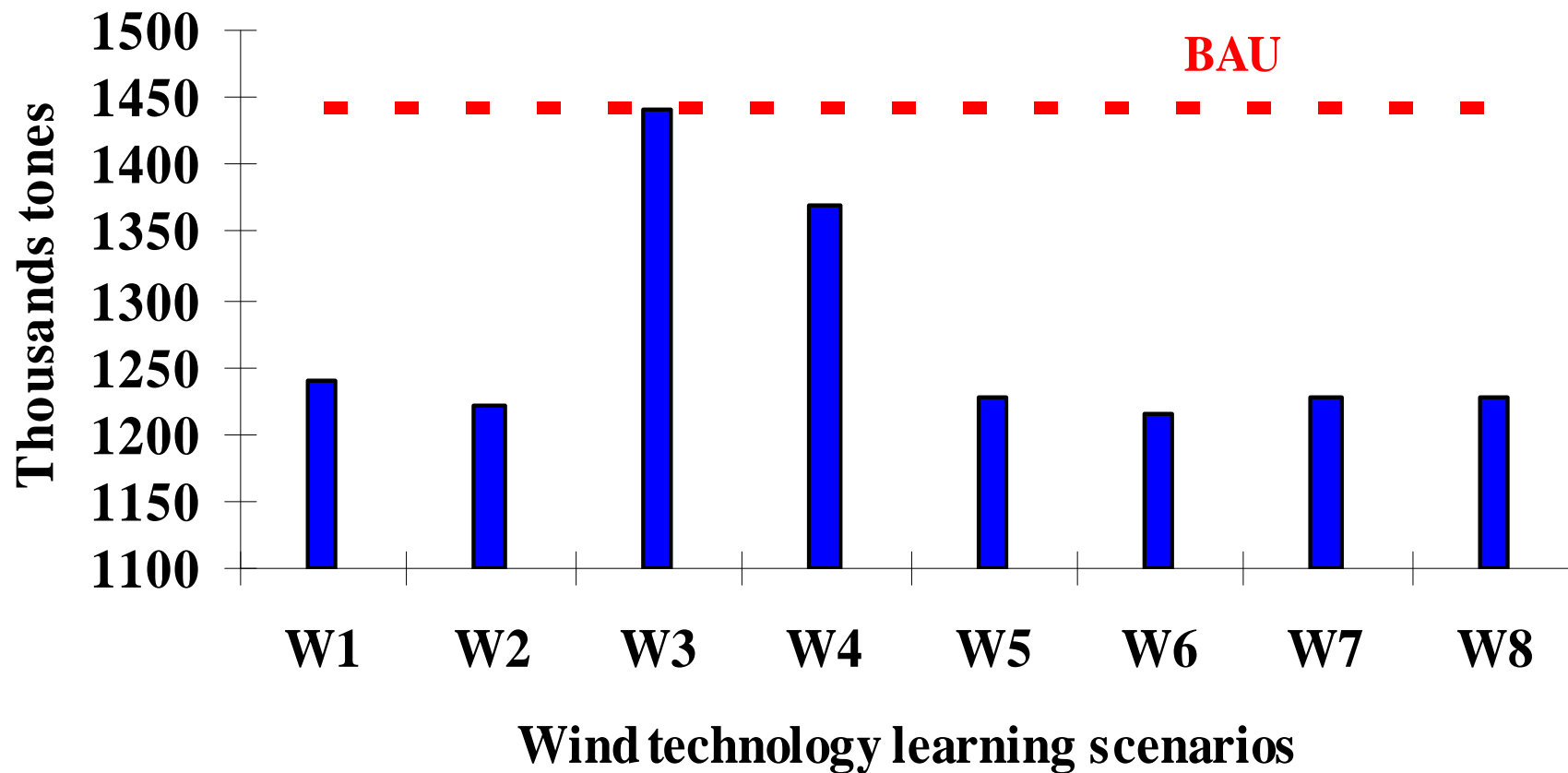
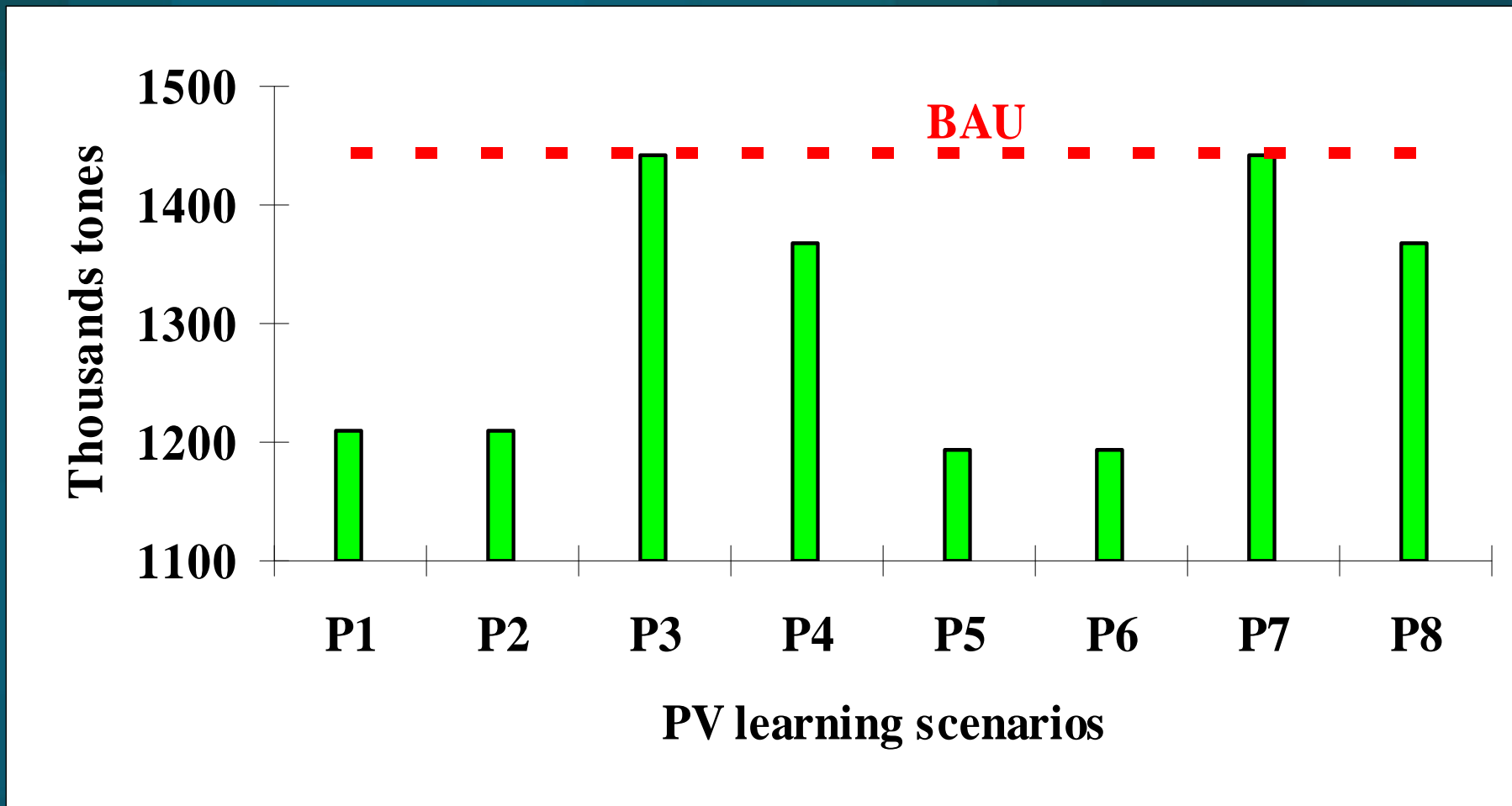


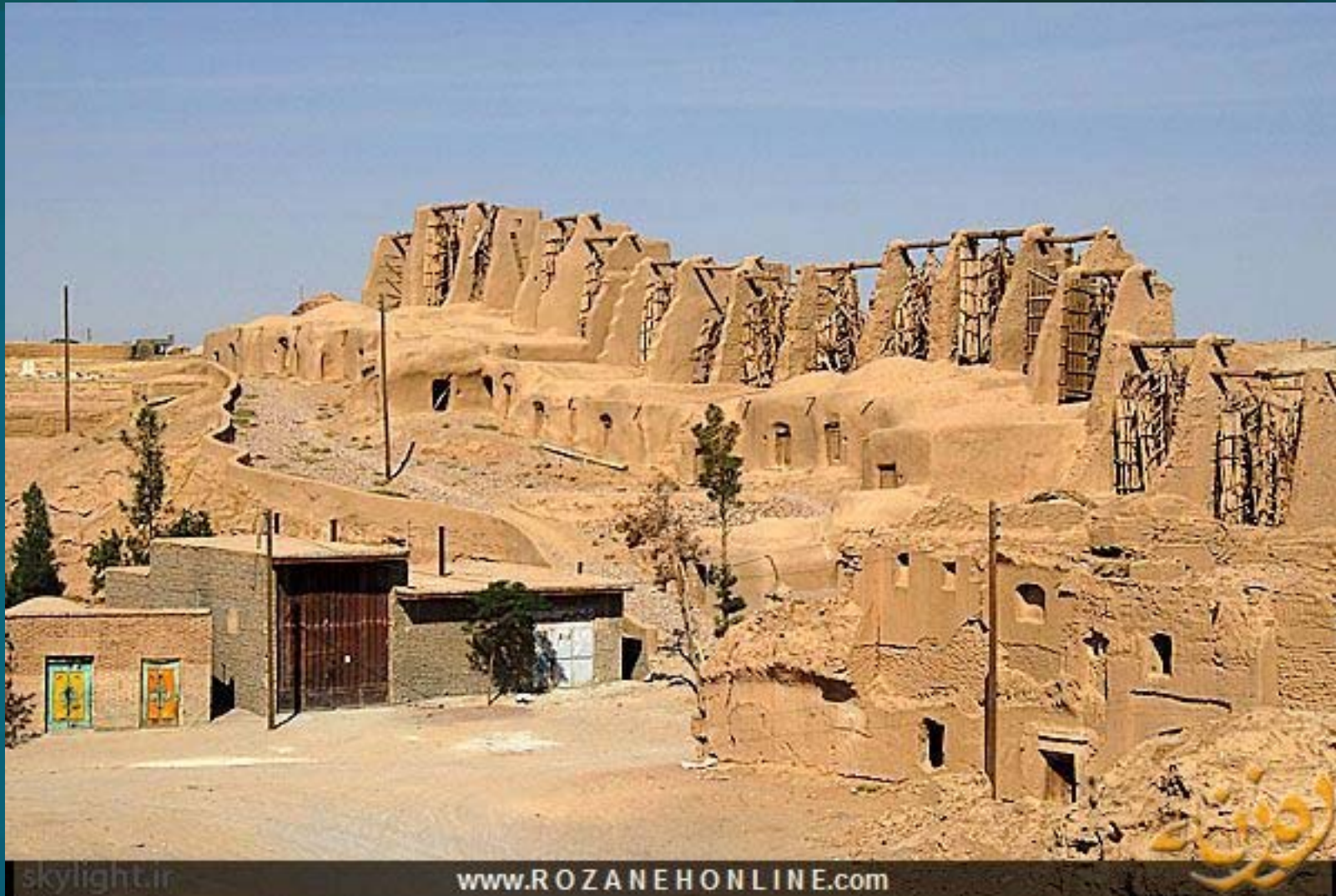
Figure 13. Power sector accumulated CO<sub>2</sub> emission under PV technology learning scenarios



# Concluding remarks

- Regarding wind energy technology, the results are highly sensitive to PR whether energy prices are subsidized or not.
- Solar energy technology (PV system) can be a promising energy supply source for the future provided that PR=80%.
- Energy price distortions exacerbate the learning process significantly.

# The first generation of wind turbines as an Iranian national heritage !

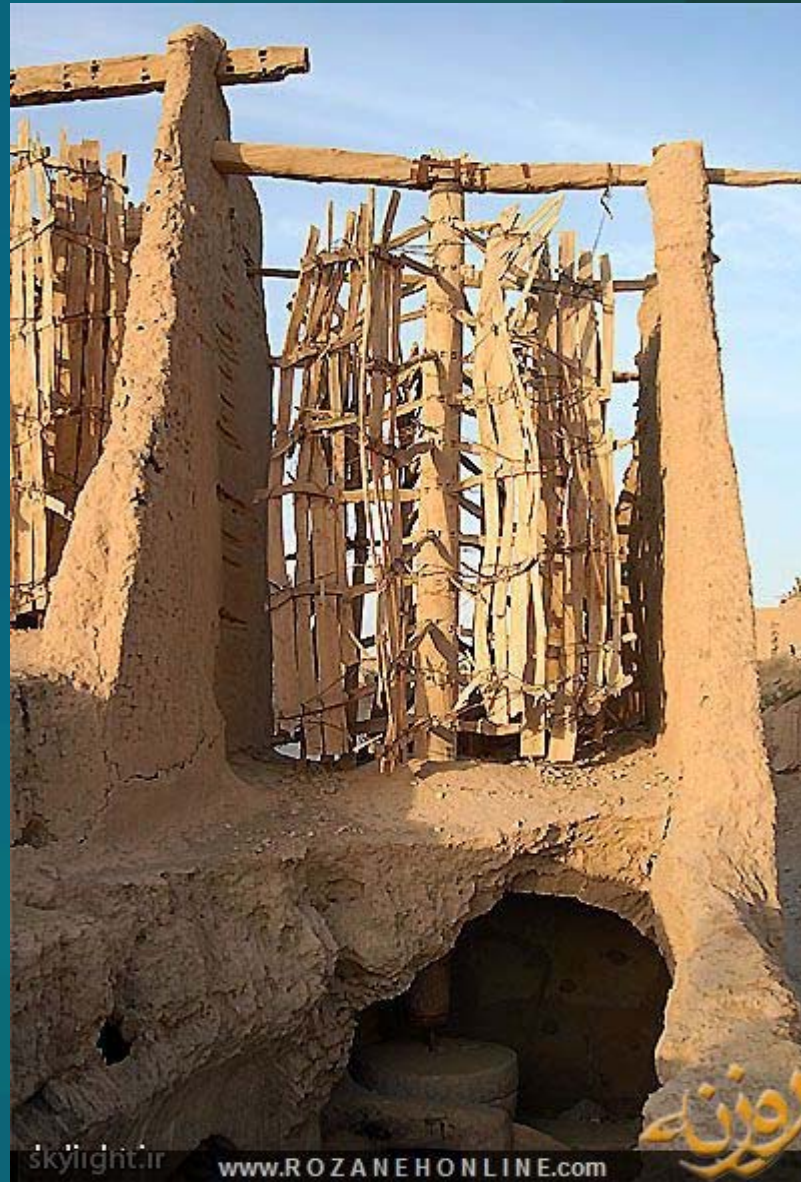


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