

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

α = Learning rate

PR= Progress ratio

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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

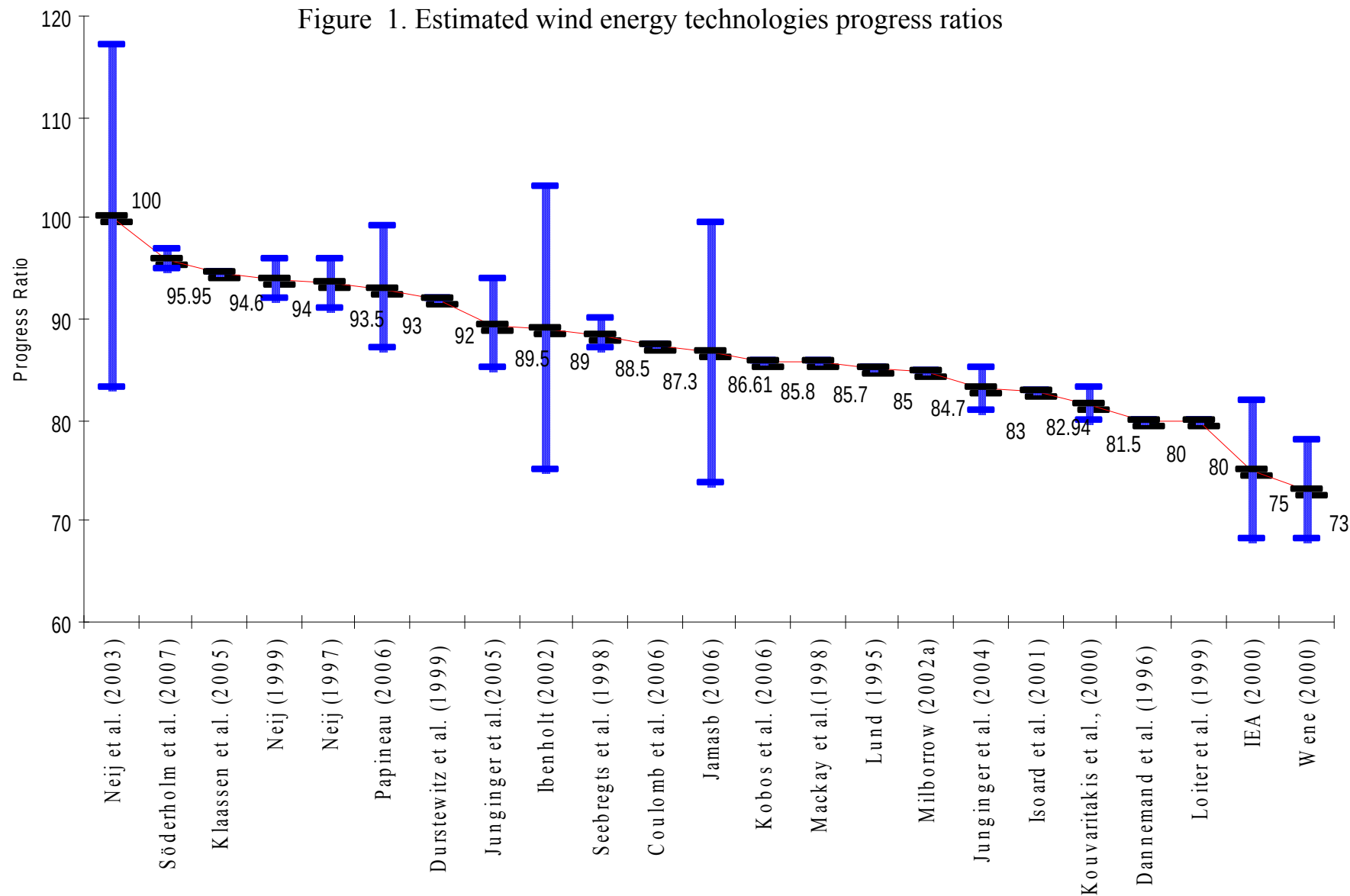
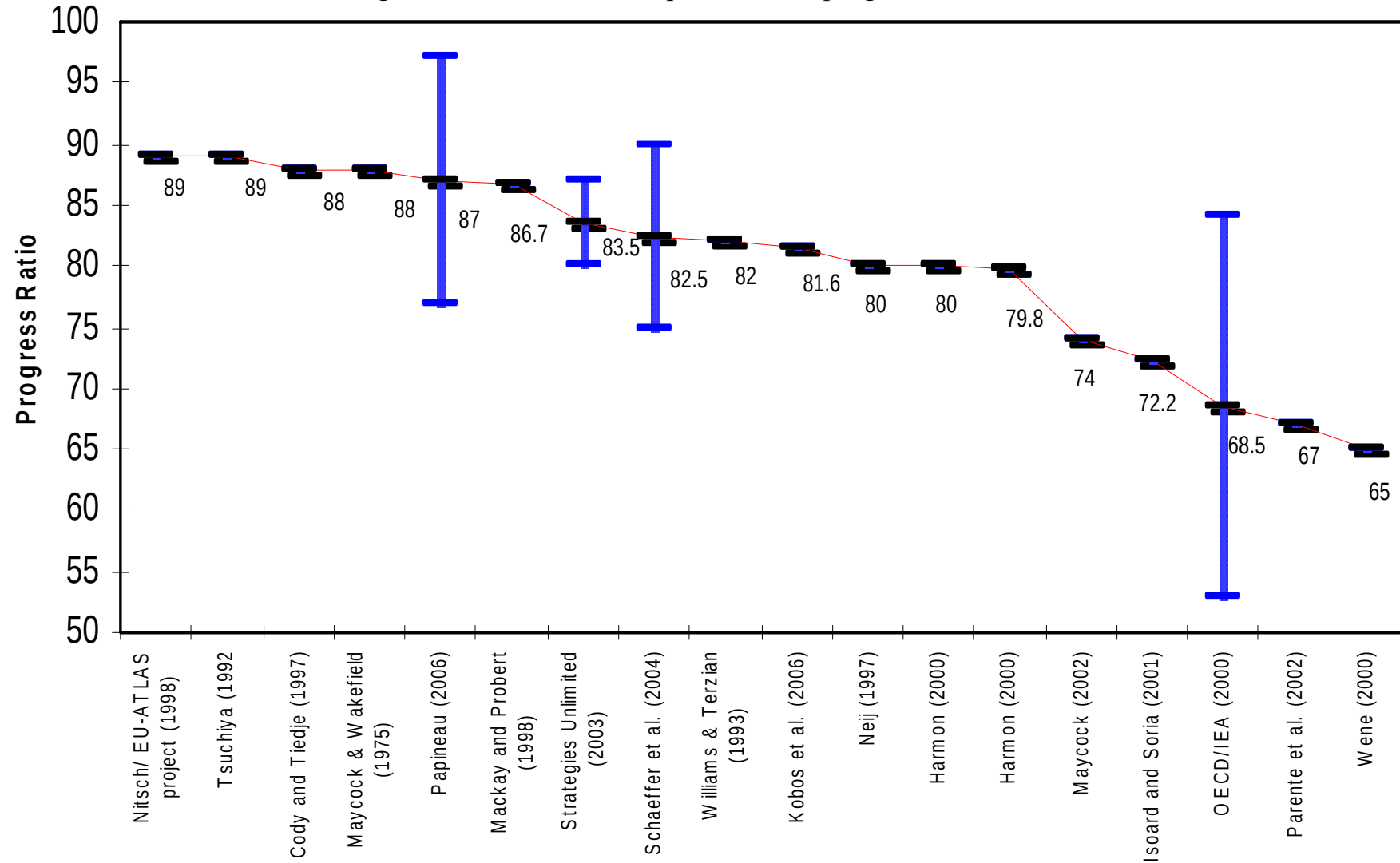


Figure 2. Estimated solar photovoltaic progress ratios



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

τ = The number of periods in the planning horizon

π = 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:

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

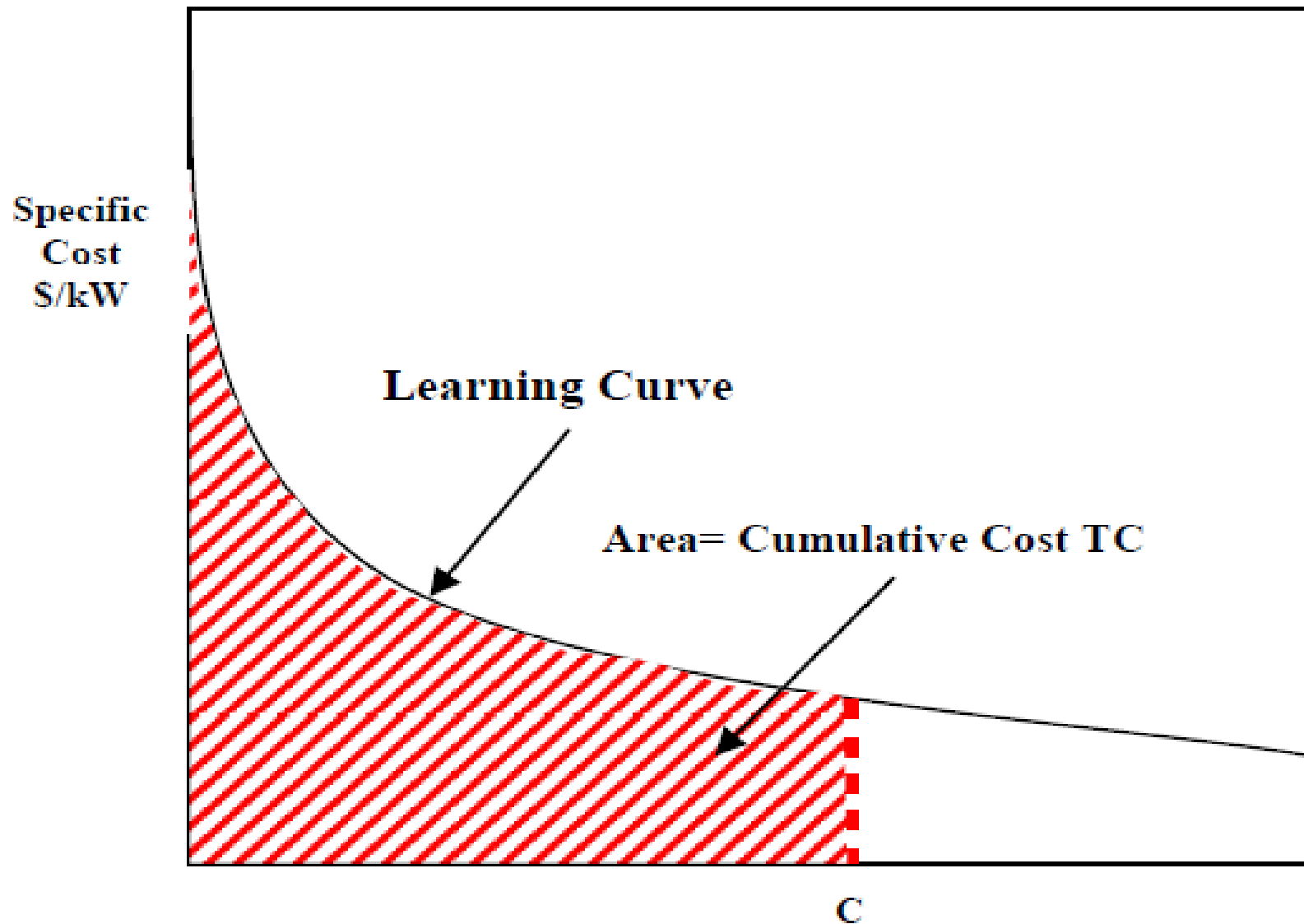
Learning curve modeling (con't)

- 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:

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

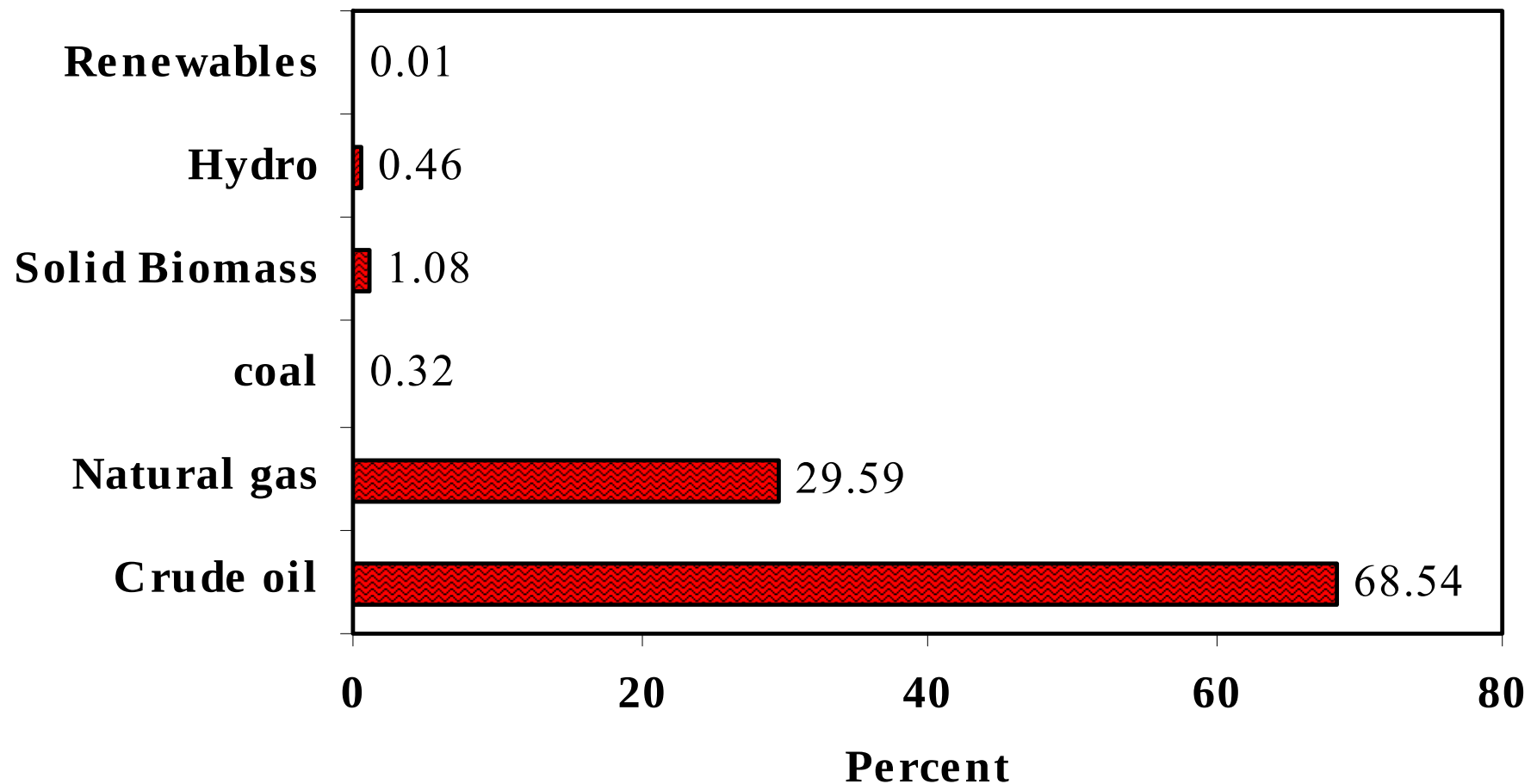
$$C_{i,k} = \left(\frac{(1-b)}{a} (TC_{i,k}) \right)^{\frac{1}{1-b}}$$

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



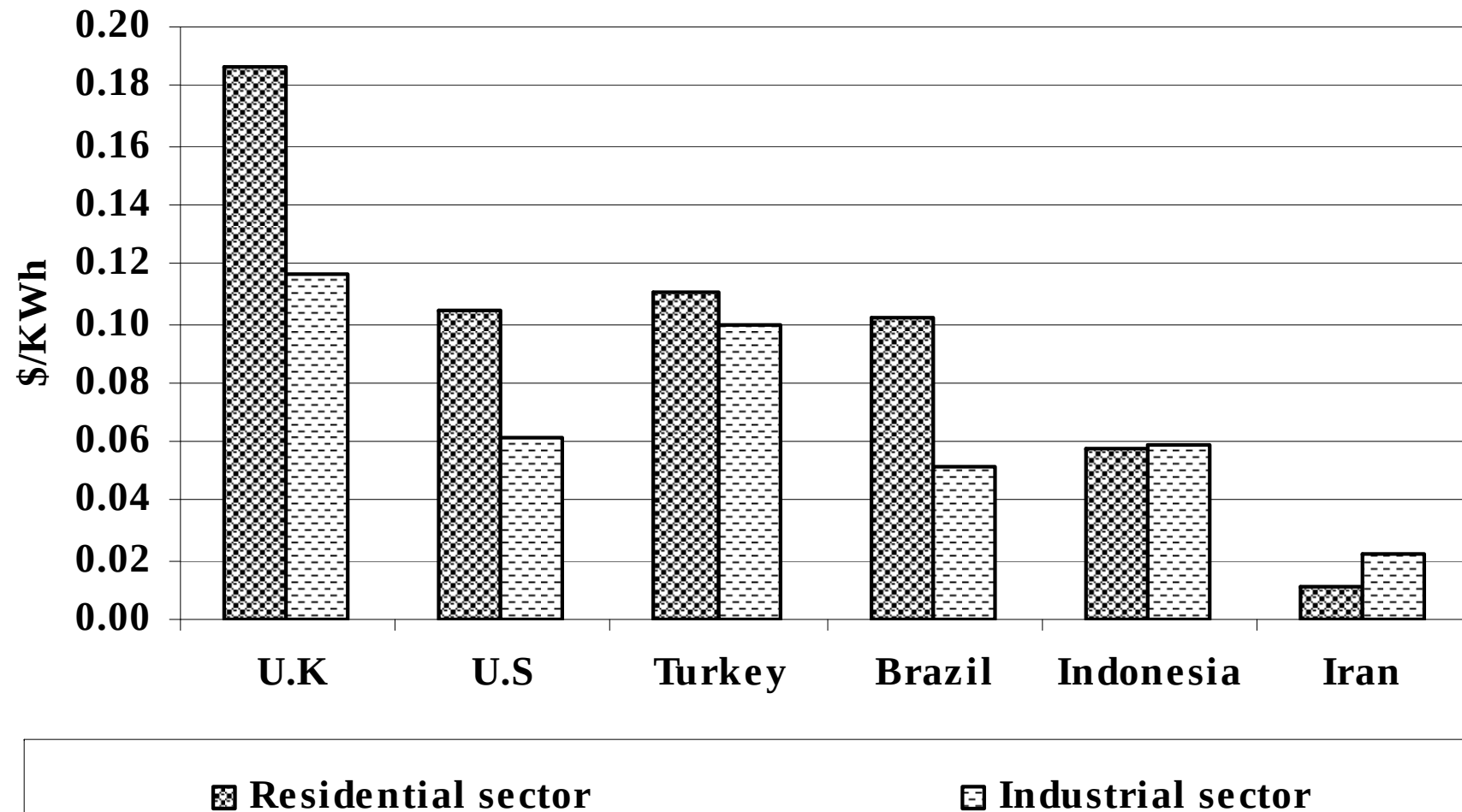
Main characteristics of the Iranian electricity sector

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



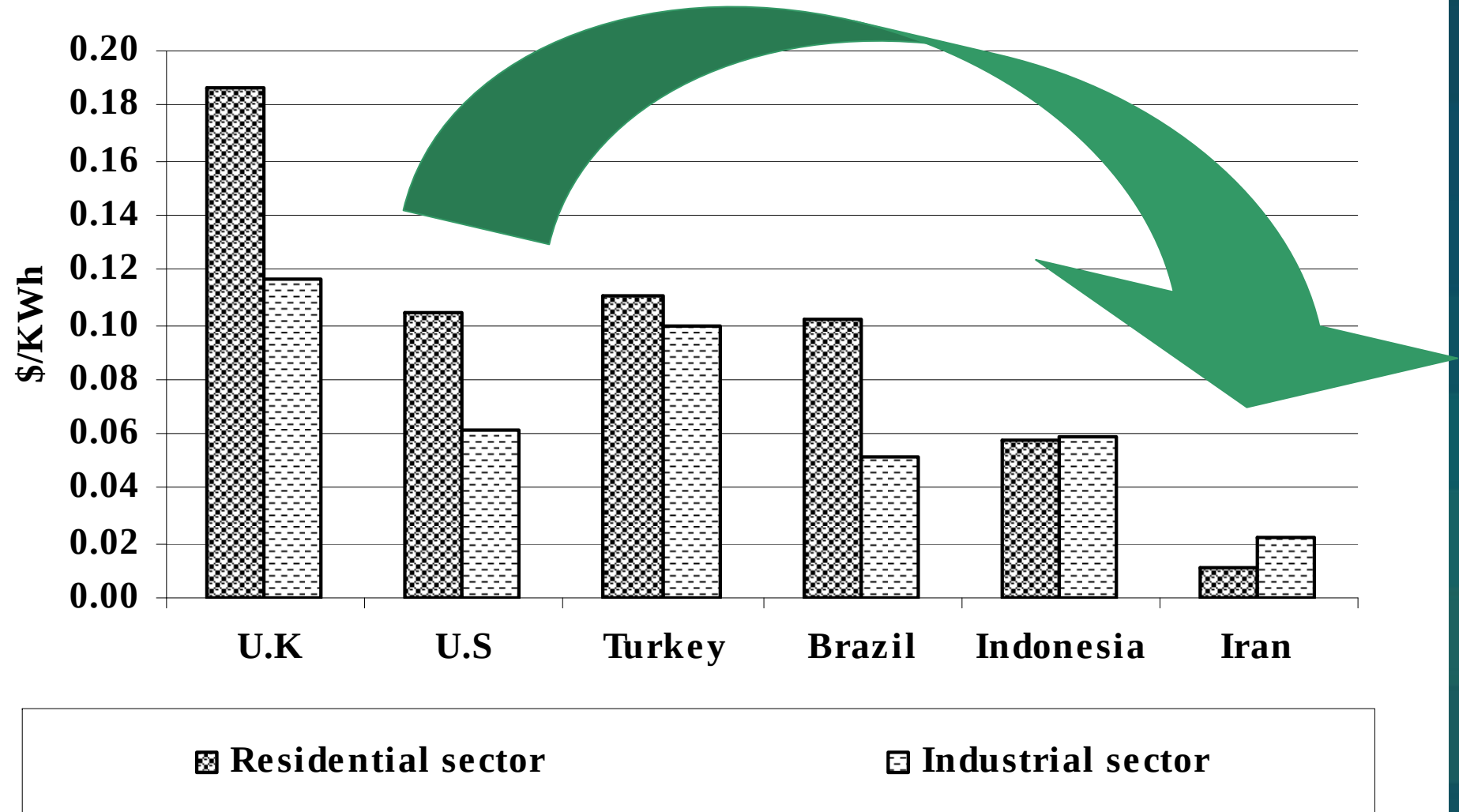
Main characteristics of the Iranian electricity sector

Figure 5. Energy subsidization and price distortions



Main characteristics of the Iranian electricity sector

Figure 5. Energy subsidization and price distortions

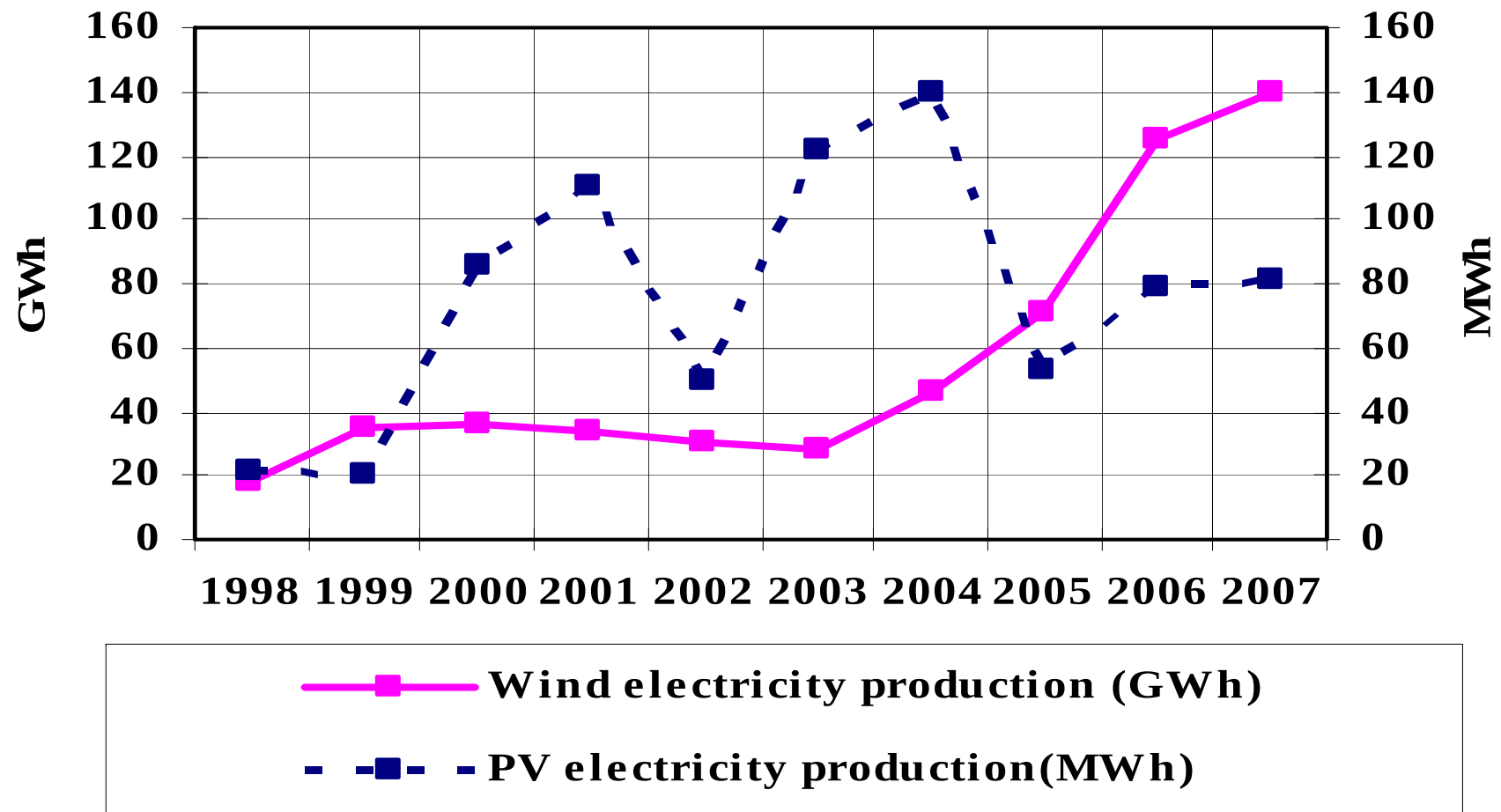


Main characteristics of the Iranian electricity sector

Power Plant	CO ₂ emission	Share in total power
	Million tones	sector CO ₂ 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

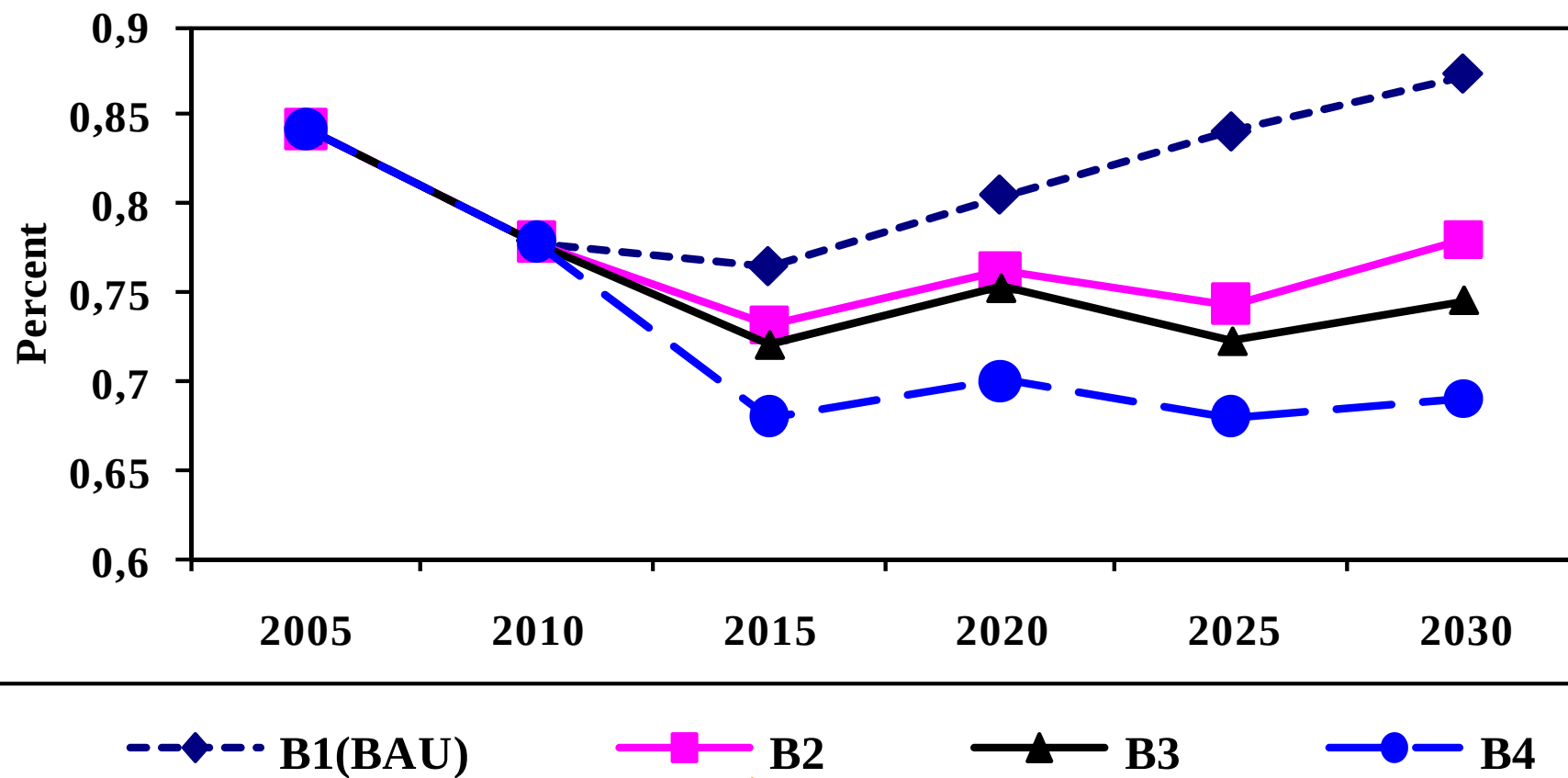


Case study

- 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 ₂ 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)	+	-

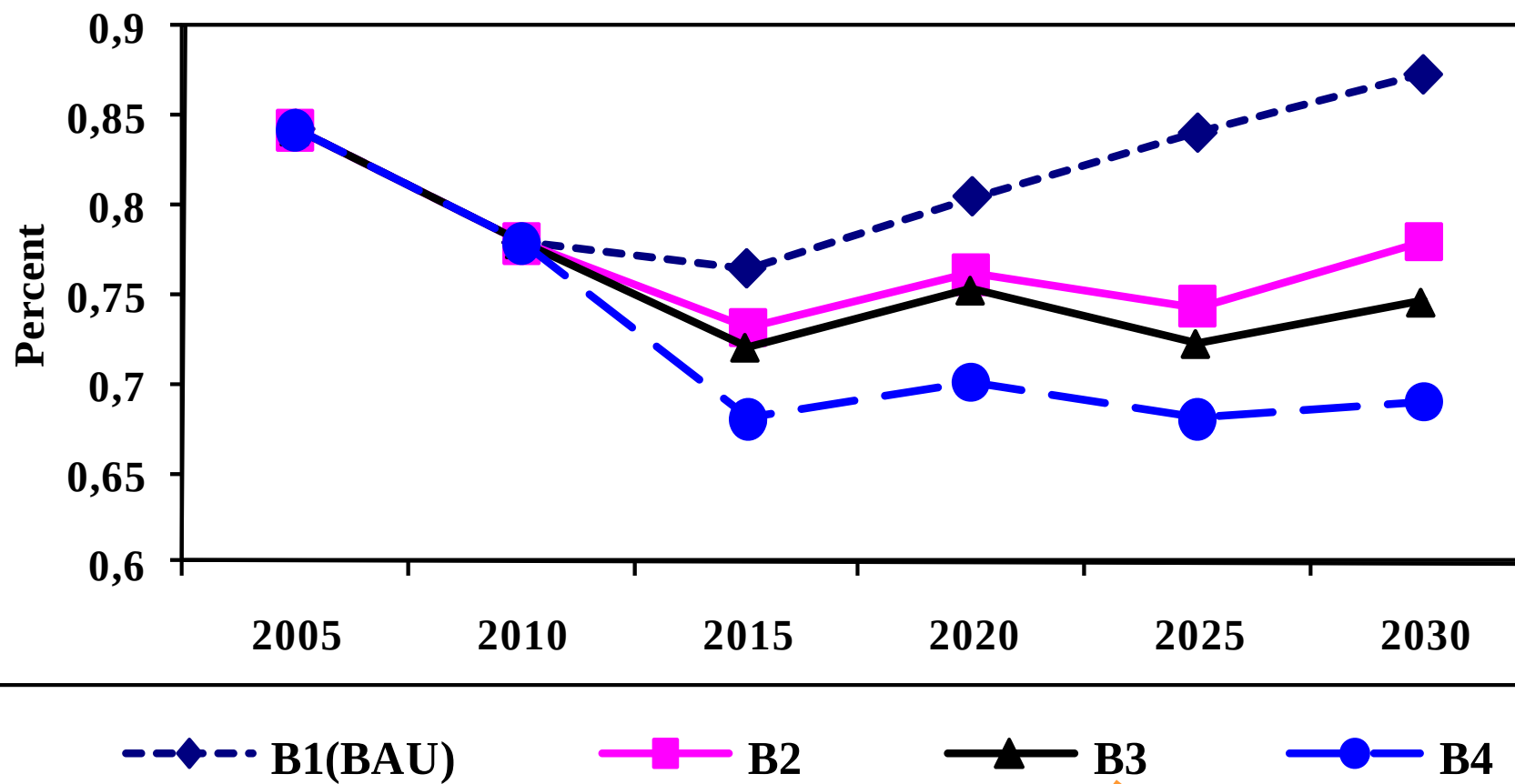
Figure 7. The share of thermal power plants under different non-learning scenarios



Emission taxation

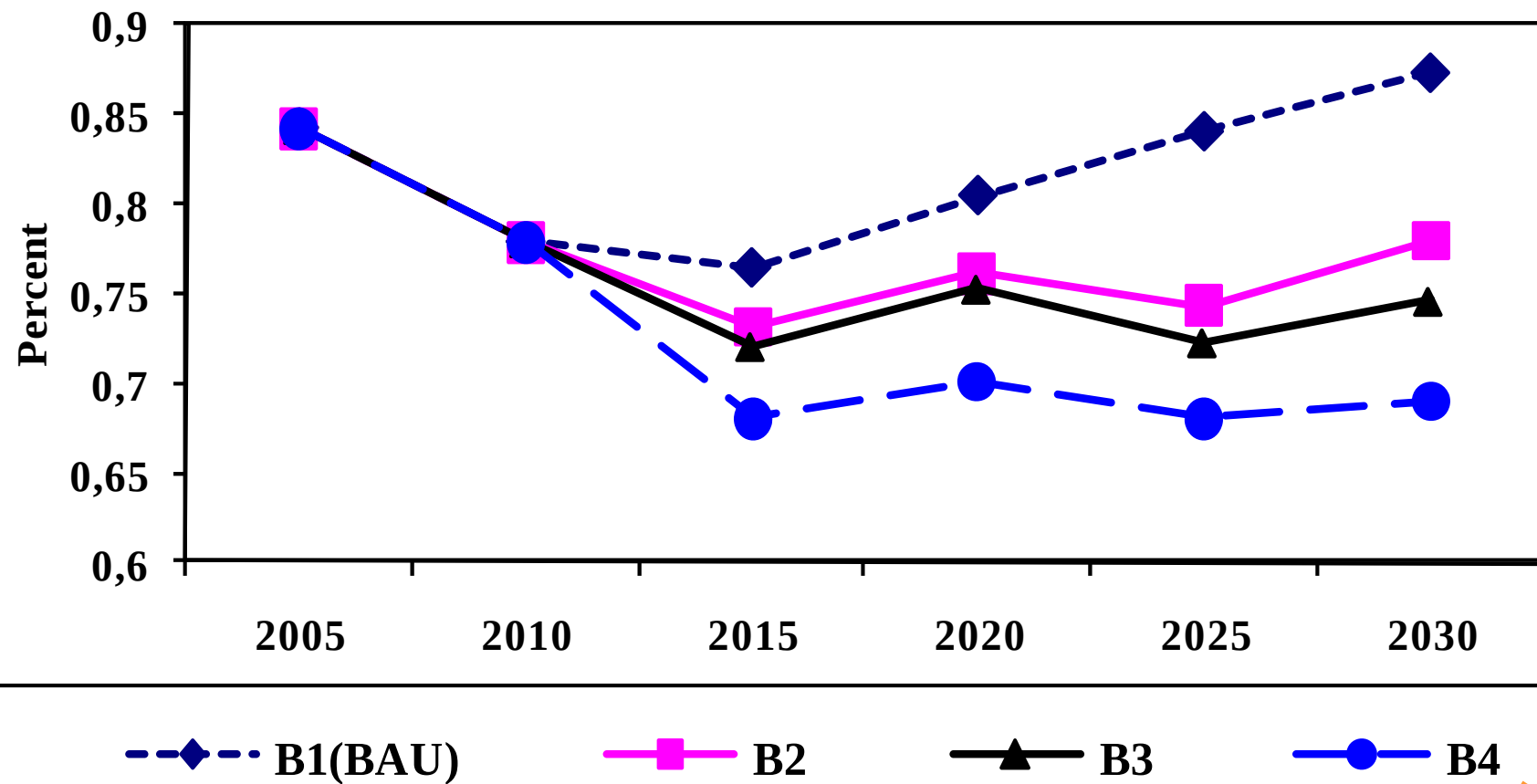
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Figure 7. The share of thermal power plants under different non-learning scenarios



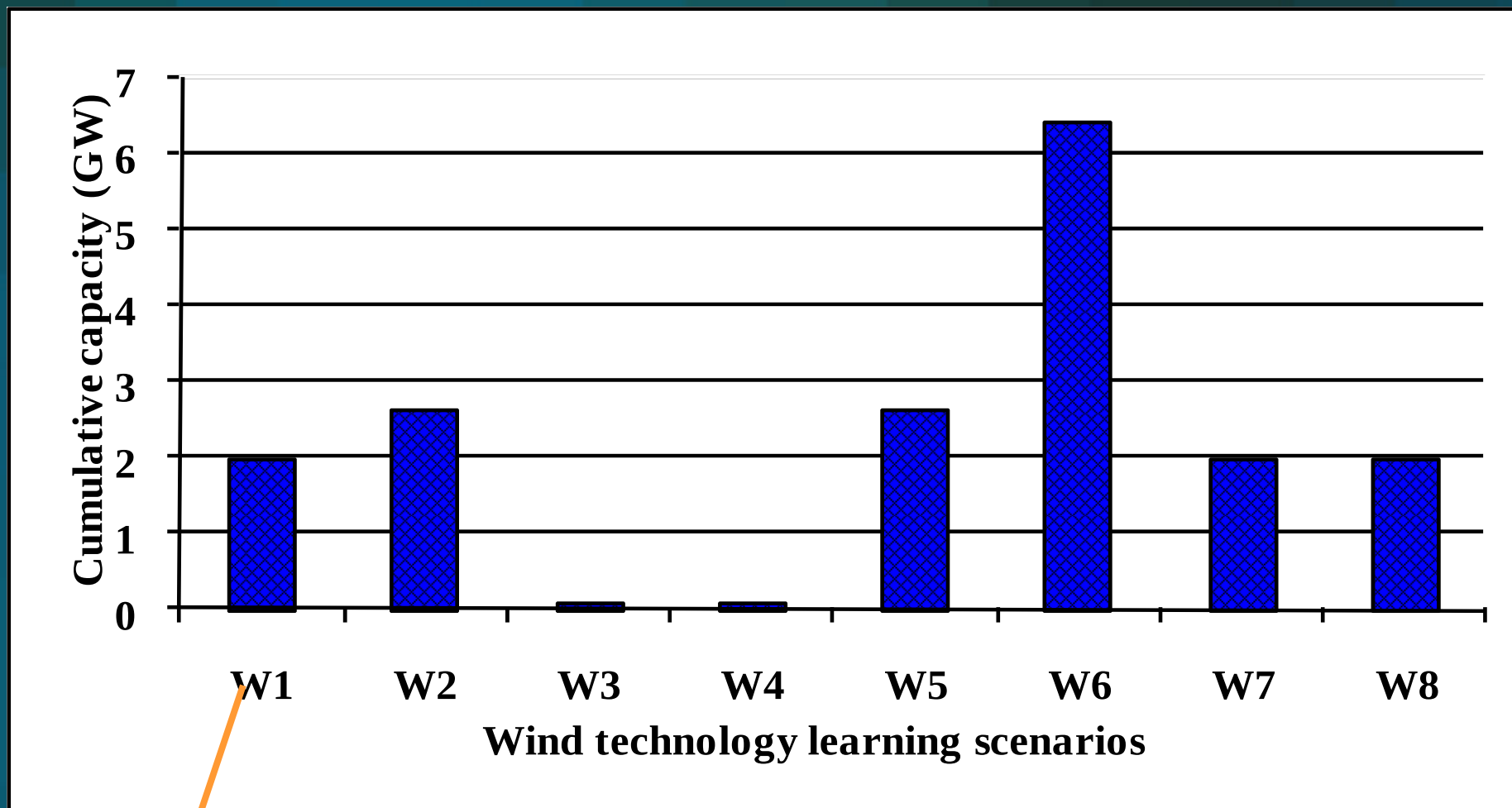
Subsidy phase-out

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



Emission taxation + Subsidy phase-out

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



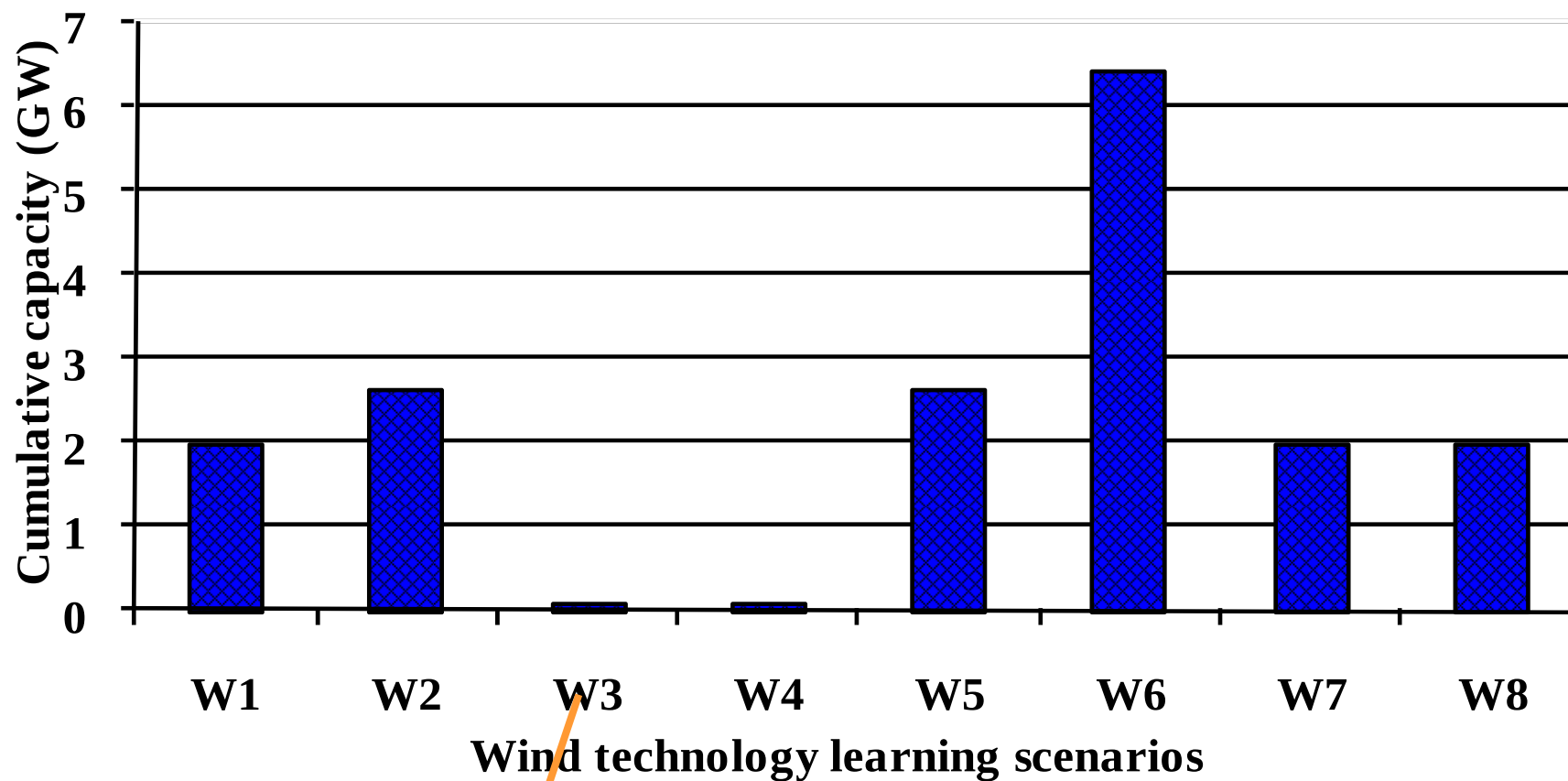
No emission taxation + Subsidy phase-out

(PR=86%)

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



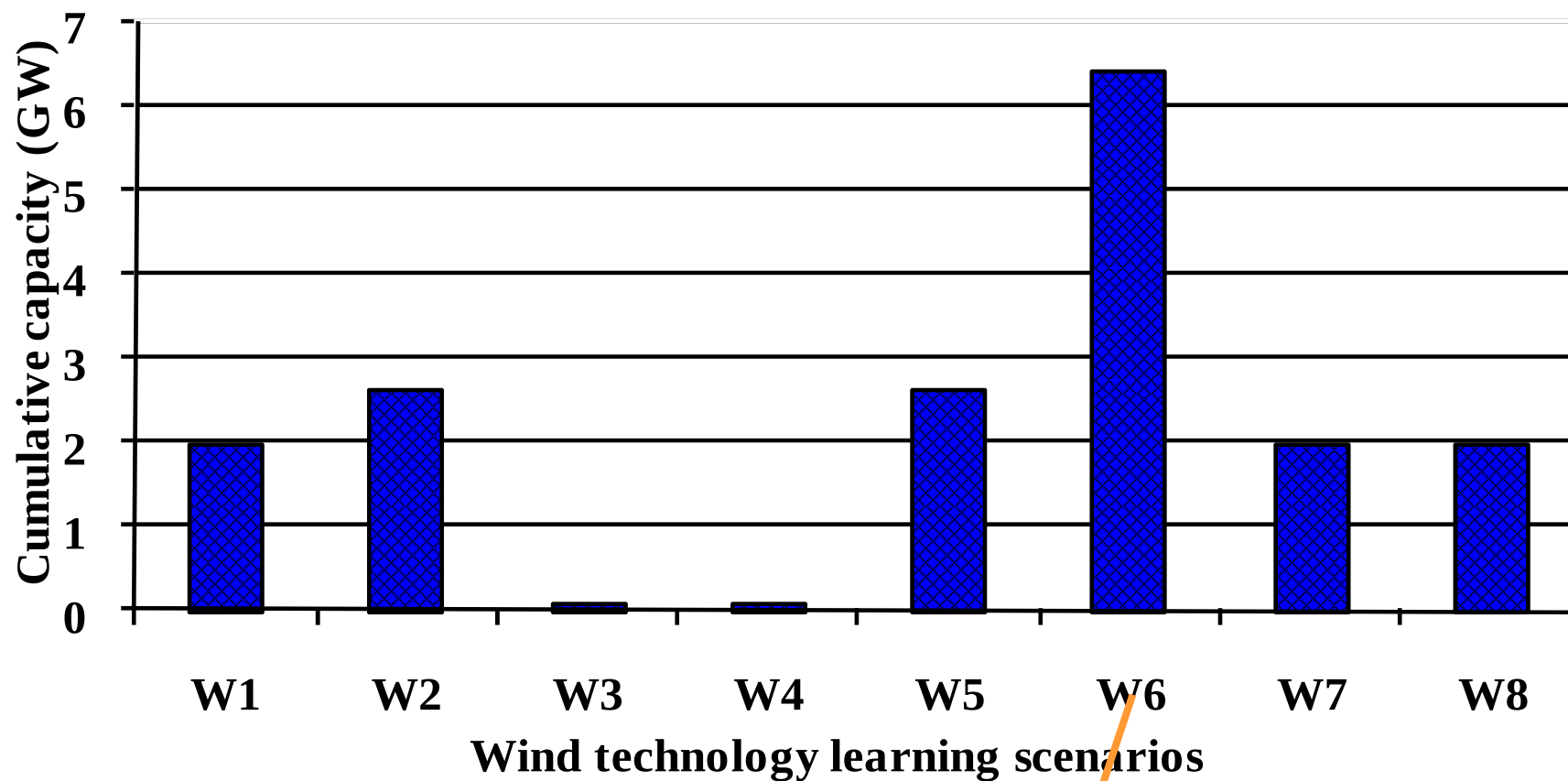
No emission taxation + Energy subsidization

(PR=86%)

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



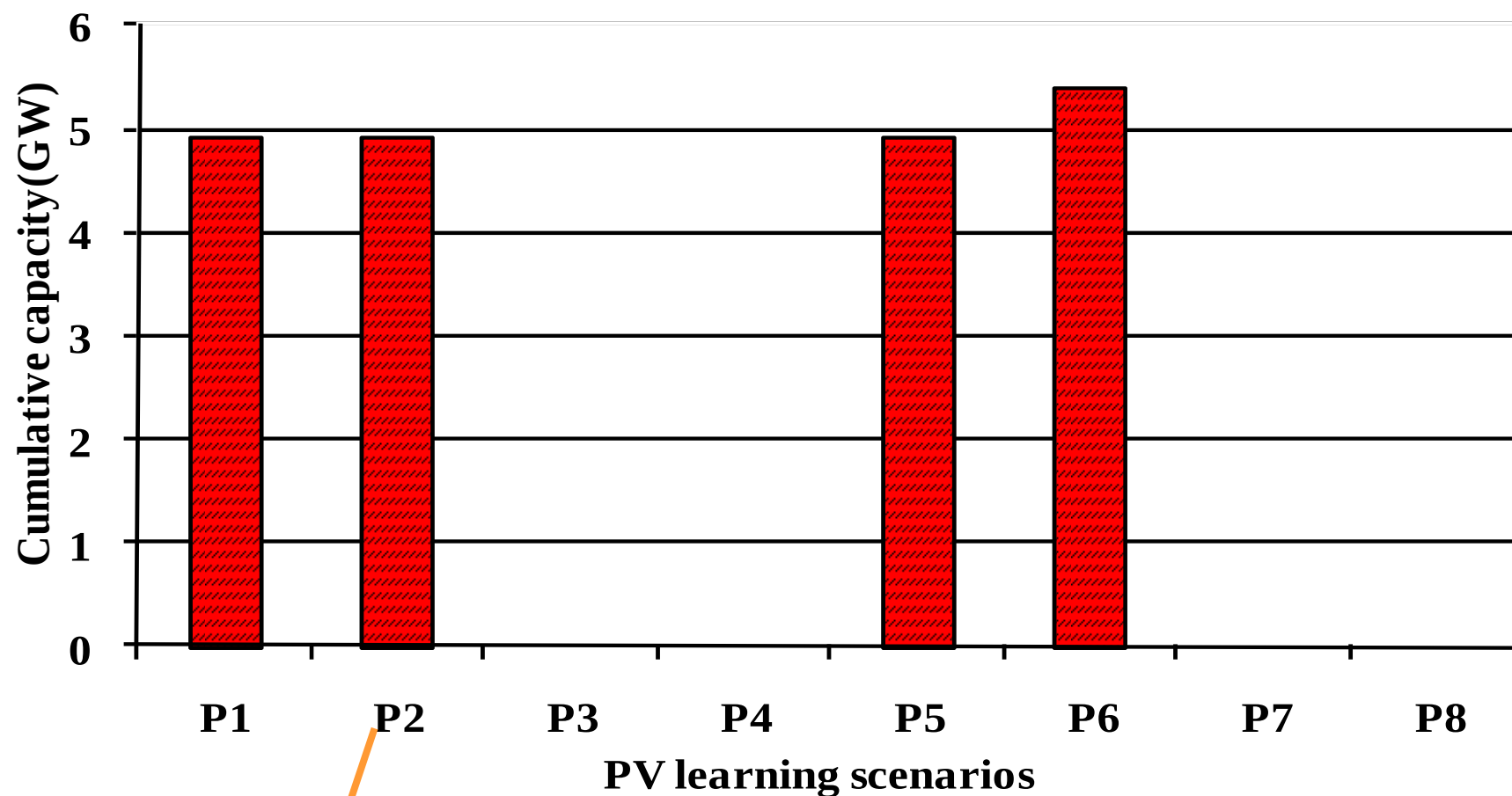
Emission taxation + Subsidy phase-out

(PR=73%)

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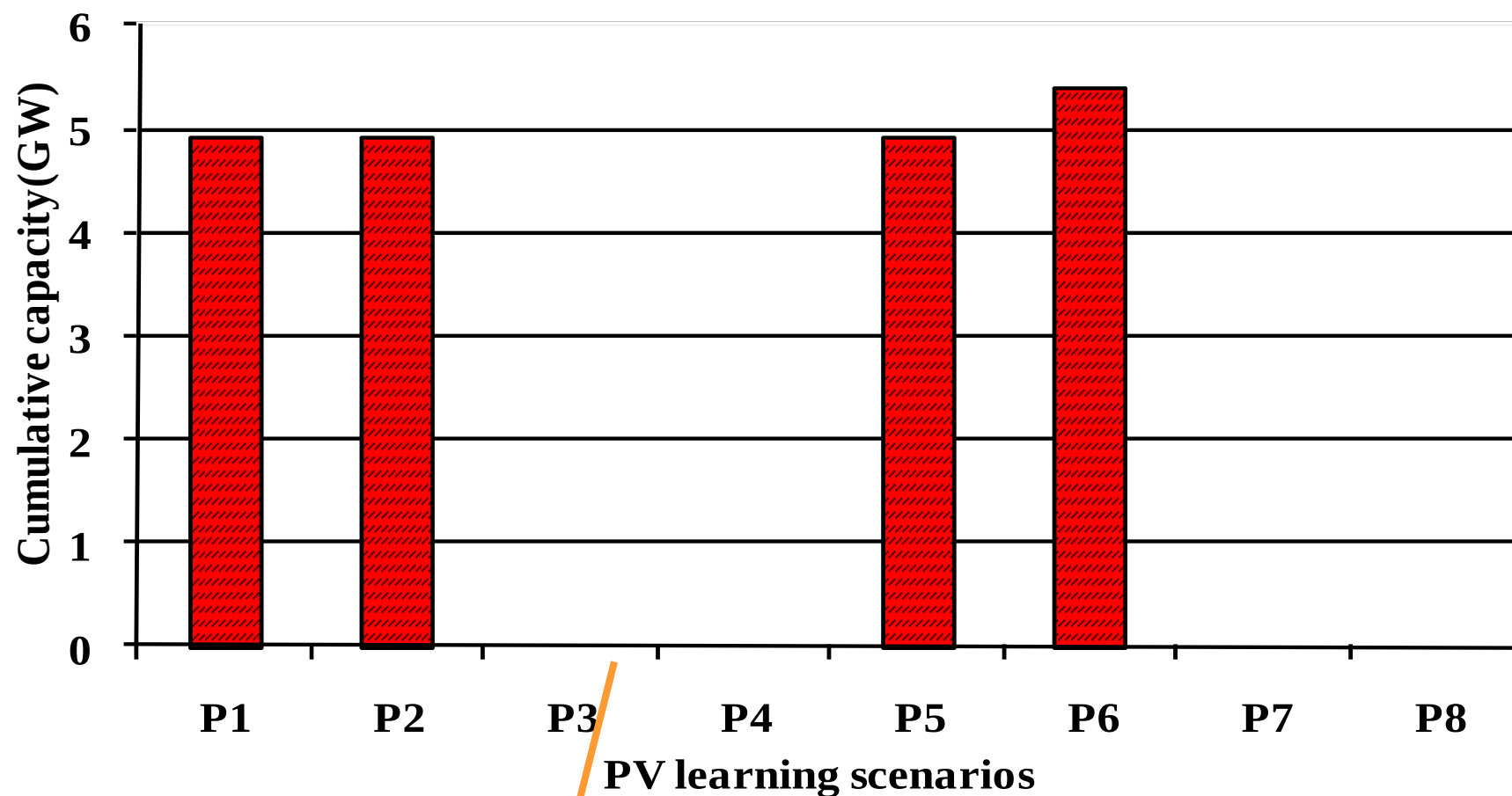
Figure 9. The effect of learning by doing on PV technology installed capacity



Emission taxation + Subsidy phase-out

(PR=80%)

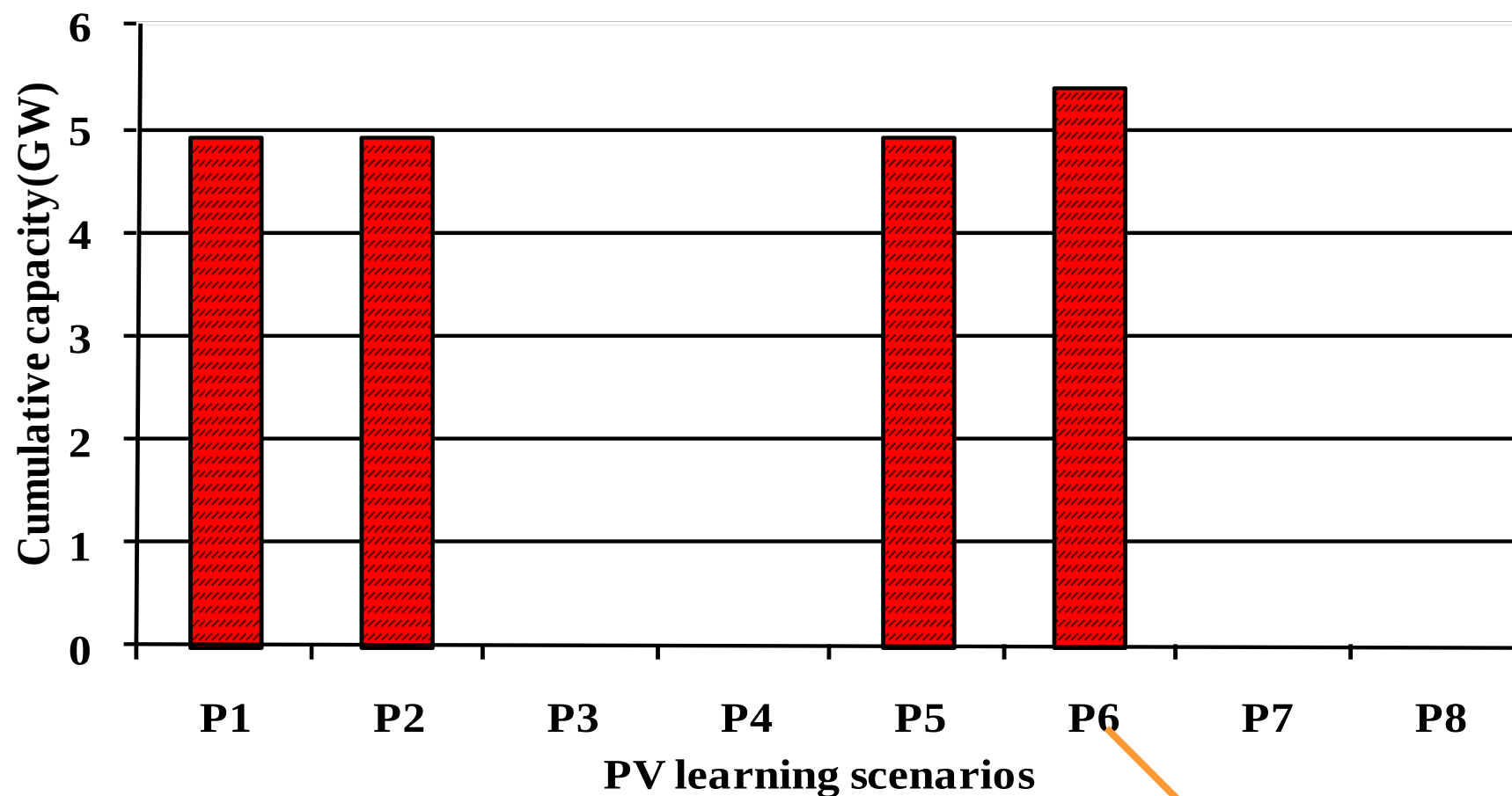
Figure 9. The effect of learning by doing on PV technology installed capacity



No emission taxation + Energy subsidization
(PR=80%)

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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

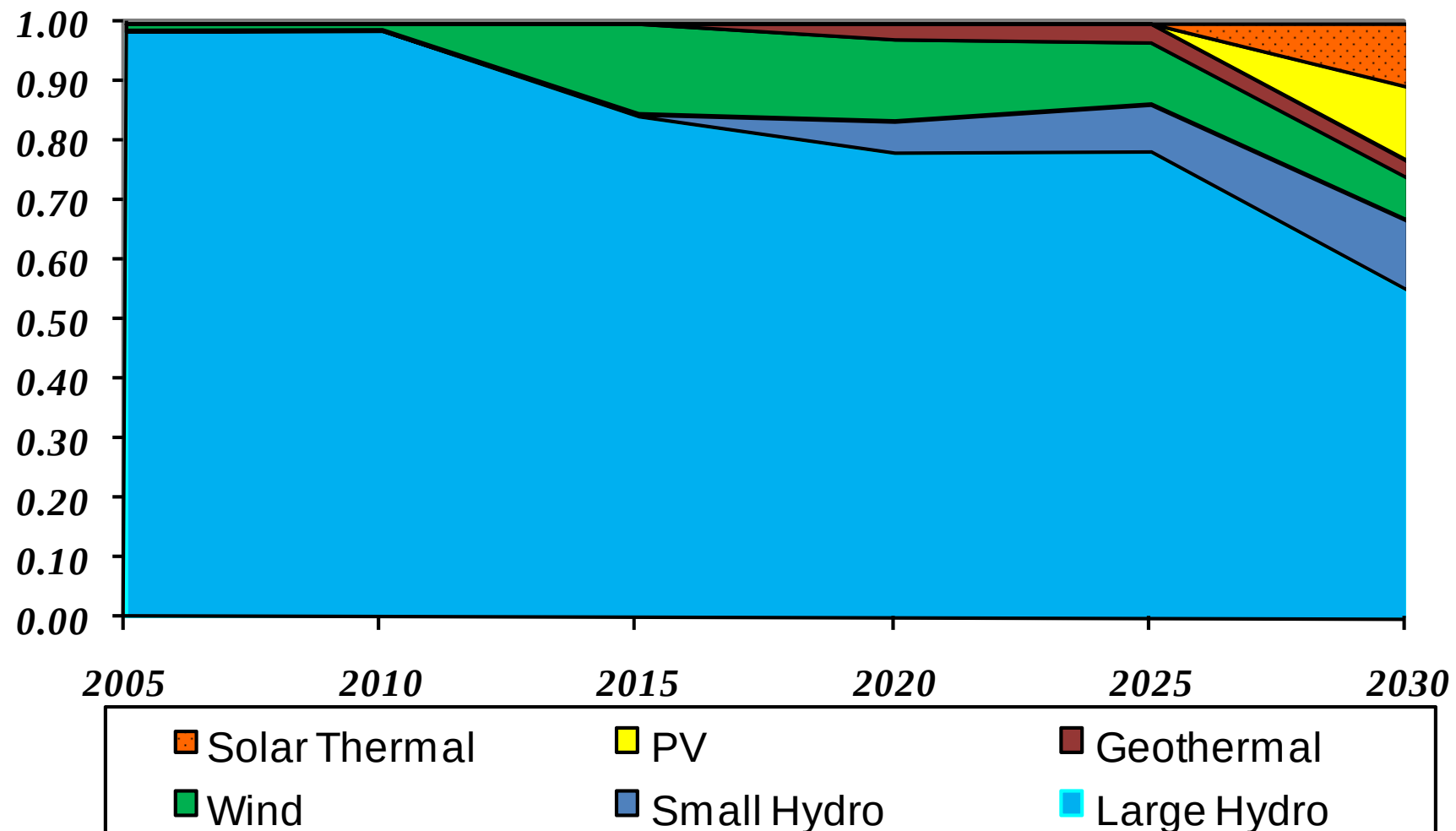


Figure 11. Power sector accumulated CO₂ emission under non-learning scenarios

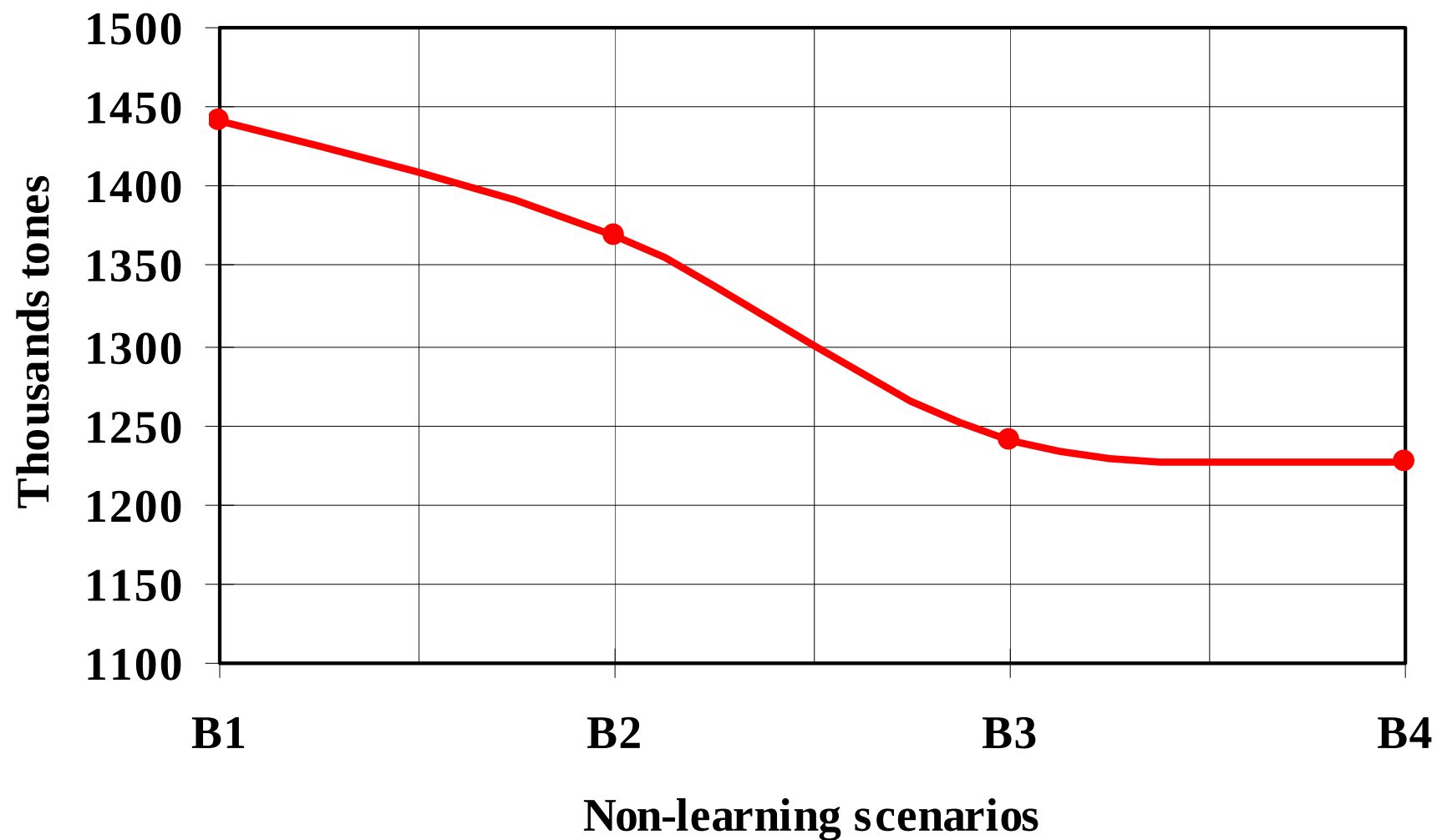


Figure 12. Power sector accumulated CO₂ emission under wind technology learning scenarios

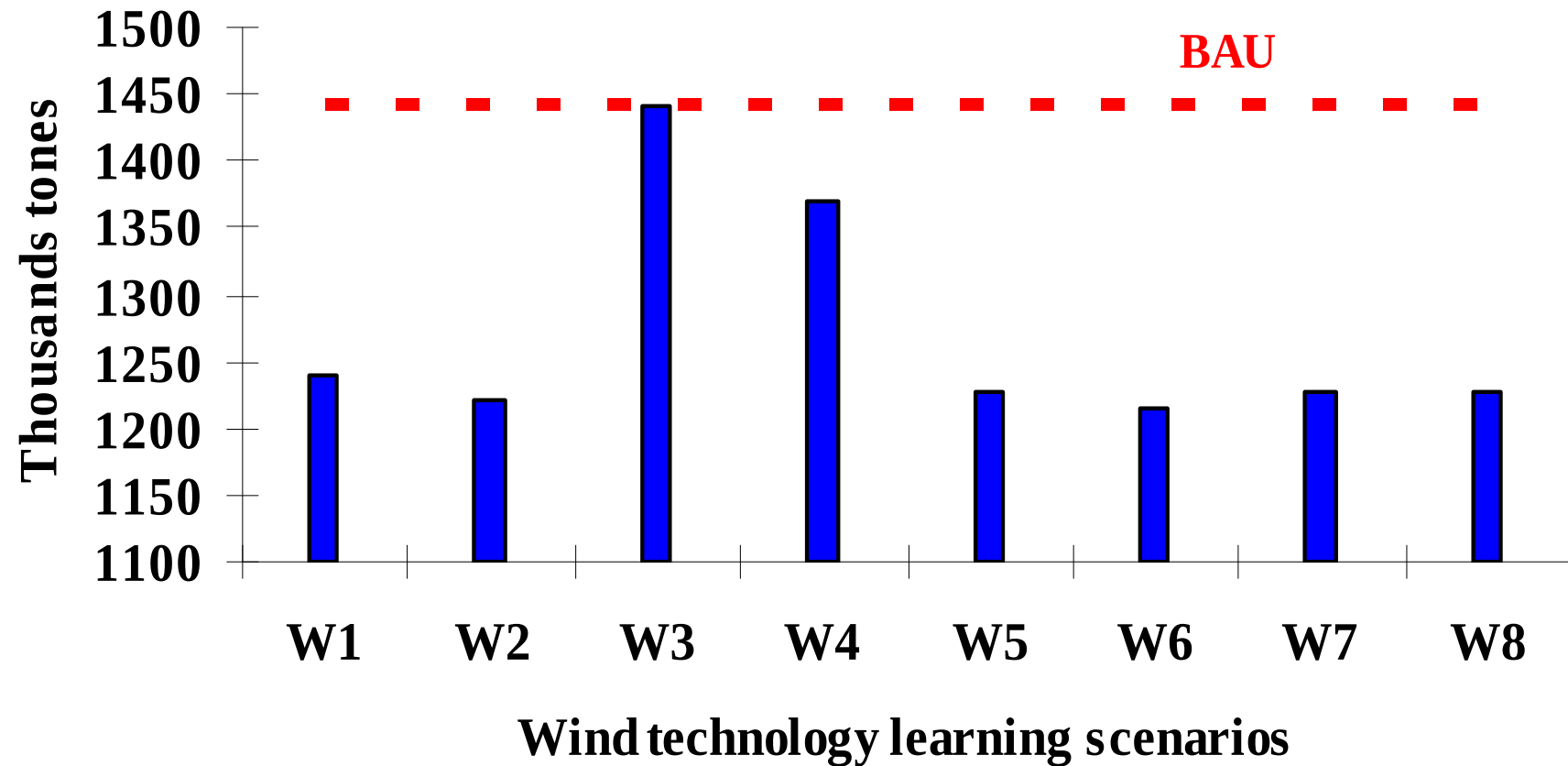
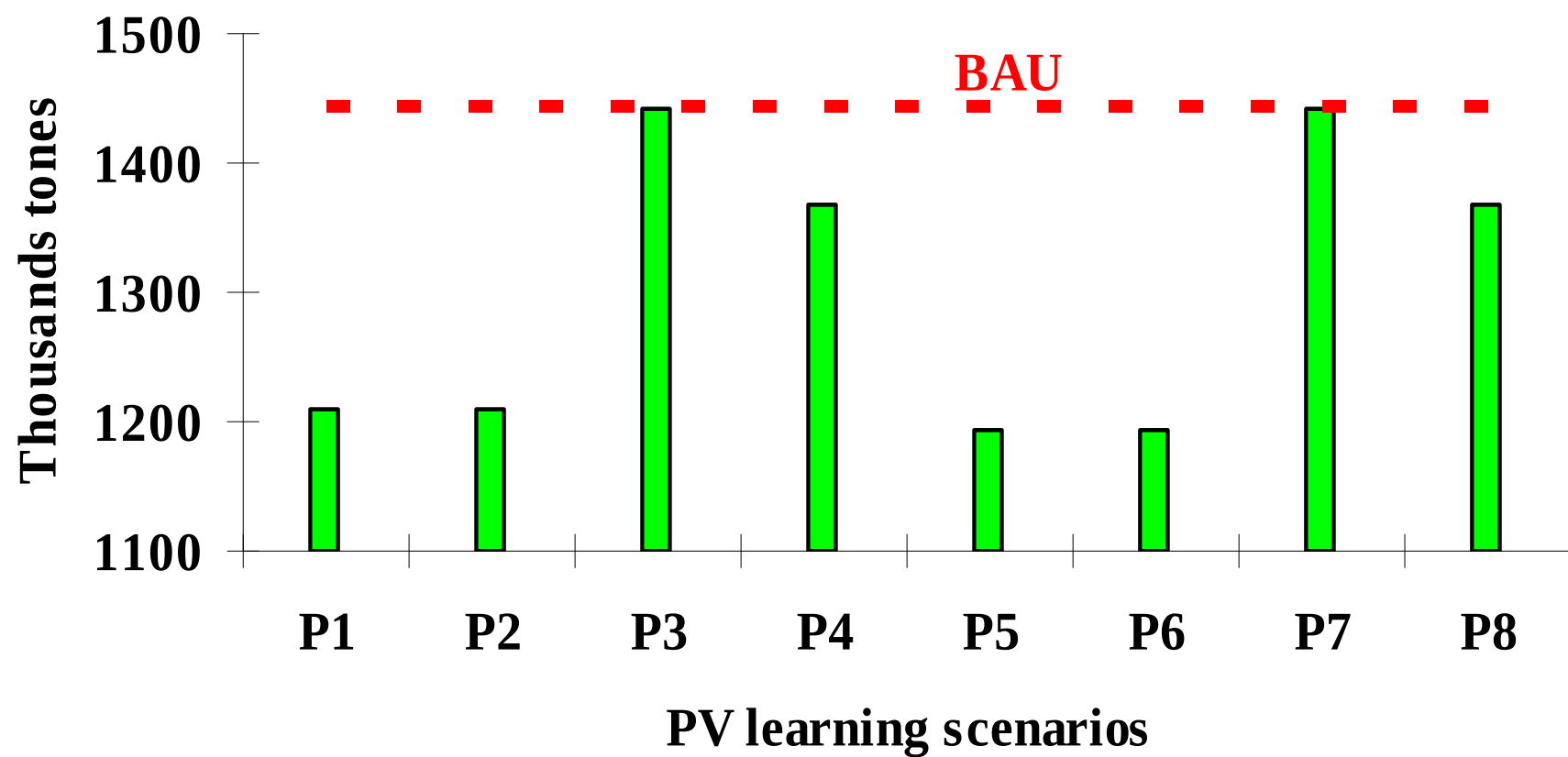


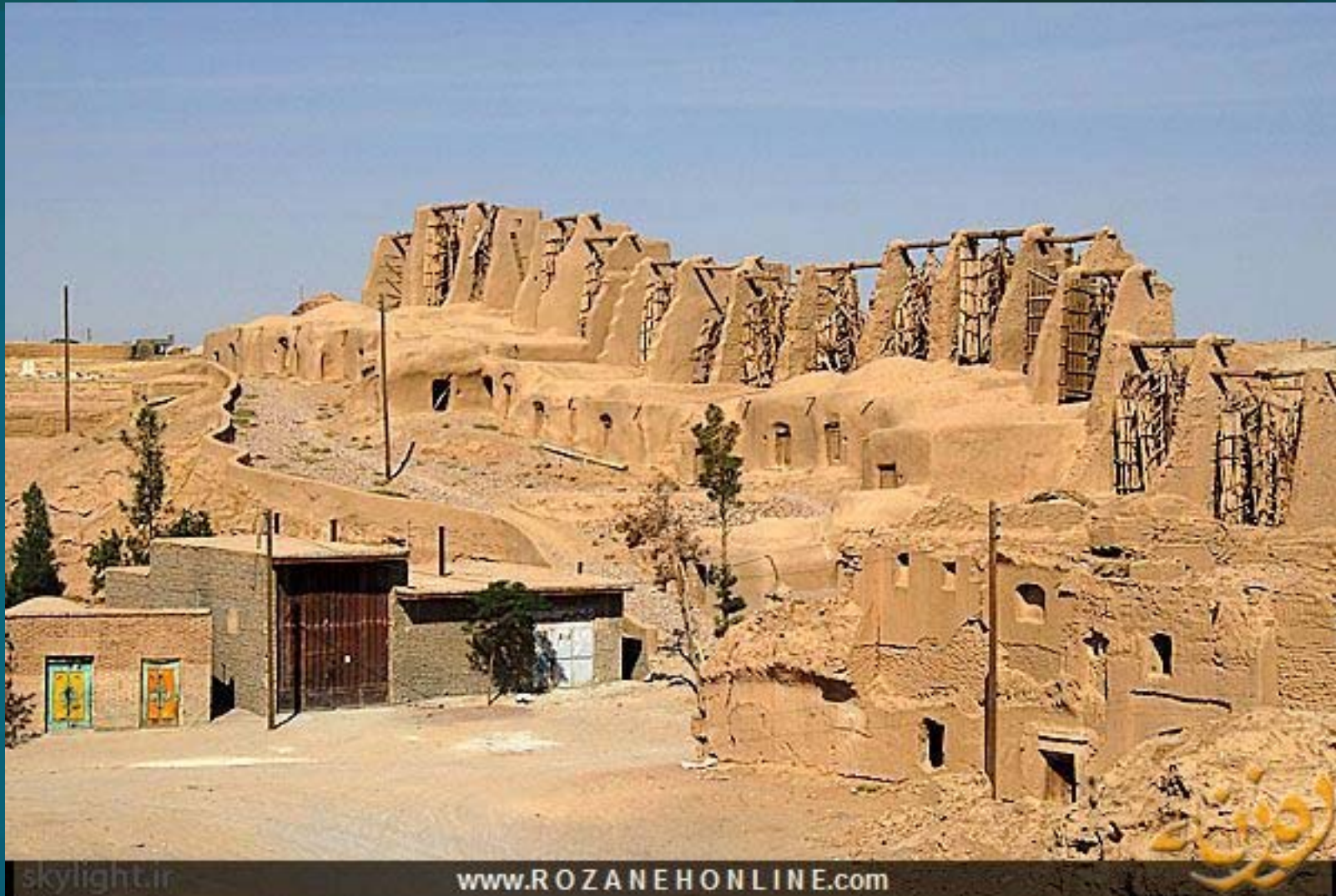
Figure 13. Power sector accumulated CO₂ emission under PV technology learning scenarios



Concluding remarks

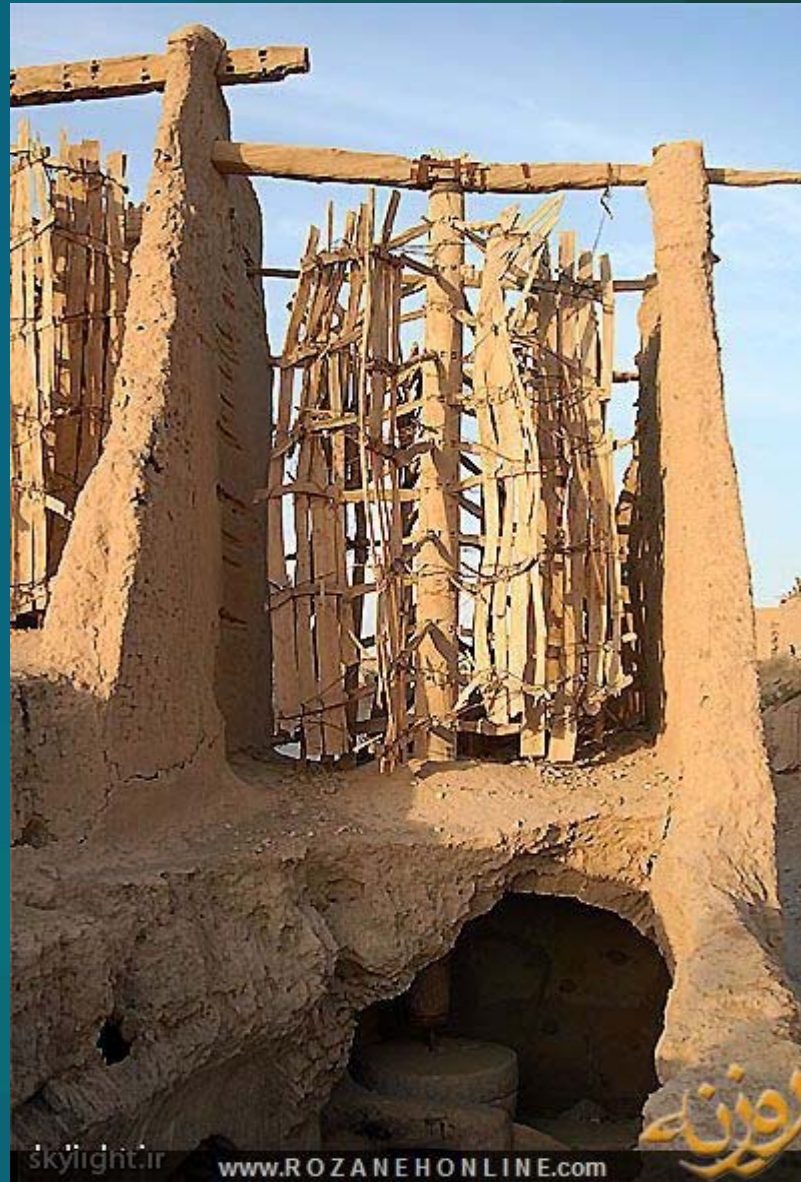
- Regarding wind energy technology, the results are highly sensitive to PR whether energy prices are subsidized or not.
- Solar energy technology (PV system) can be a promising energy supply source for the future provided that $PR=80\%$.
- Energy price distortions exacerbate the learning process significantly.

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



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