Endogenized Learning in MARKAL

Leonardo Barreto [a], Socrates Kypreos [b]
[a] ECS, International Institute for Applied Systems Analysis
[b] Energy Modelling Group, Paul Scherrer Institute

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Learning Curves

- Specific Cost (SC) as function of Cumulative Capacity (C):

$$SC(C) = a * C^{-b}$$

- Learning-by-doing index b: effectiveness of learning
- Parameter a: starting point (SC_0, C_0)
- Cumulative Capacity is a proxy for accumulated knowledge

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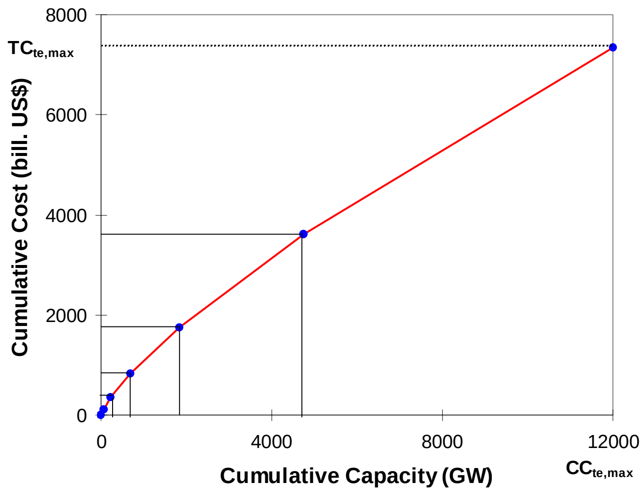
Endogenizing Learning Curves

- Non-linear, non-convex optimization
- Multiple locally optimal solutions
- No guarantee of globally optimal solution with conventional NLP solvers
  - Mixed Integer Programming (MIP)
  - Global optimization algorithms (e.g. BARON)
  - "Guided" optimization with conventional NLP algorithms (different solvers/starting points)

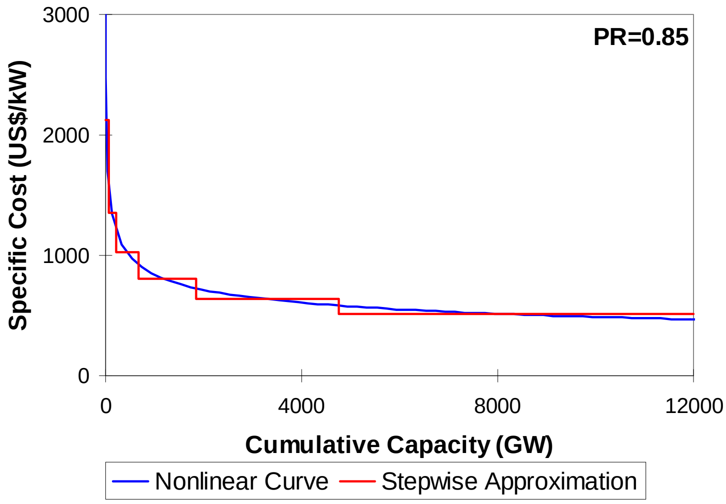
Mixed Integer Programming

- Piece-wise approximation of cumulative cost curve using binary variables to enforce sequence of segments
- Provides global optimum for the linearized problem but increases computation time

Cumulative Cost



Stepwise Specific Cost



Multi-regional Learning Spillovers

- Learning investments in one region may drive to cost reductions also in others
- With spillovers of learning:
  - deploying a technology in a region can affect technology choices in other regions
  - Carbon abatement policies in a given region may have positive effects in other regions
- This phenomenon cannot be captured by models with exogenous technical change

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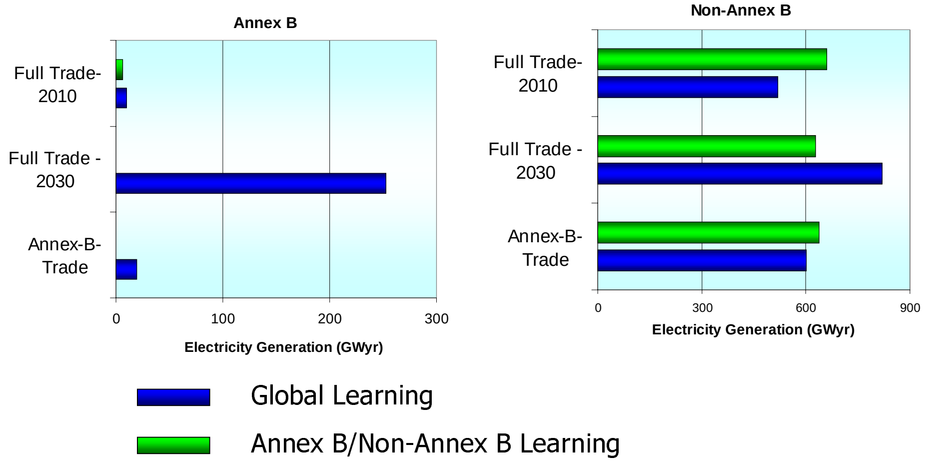
Two Scales of Learning
Solar PV-2100



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Technology Clusters

- Clusters: groups of related co-evolving technologies
- Within a cluster, technologies reinforce and cross-enhance each other
- Representation of learning spillovers within and between clusters

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Spillovers - Open Points

- This MIP formulation makes difficult to represent different configurations of spillovers between regions: ➡ Trade of learning commodities (Kanudia and Loulou)
- Spillovers between technologies should be considered (clusters): ➡ Key technologies, learning and non-learning parts (ECN)

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Support Slides

Technological Learning

- Basic mechanism of technical change
- Progress (cost/performance) requires experience
- Increasing returns: Learning-by-doing, by-searching, by-using
- Endogenized learning enables better treatment of technical change in the models

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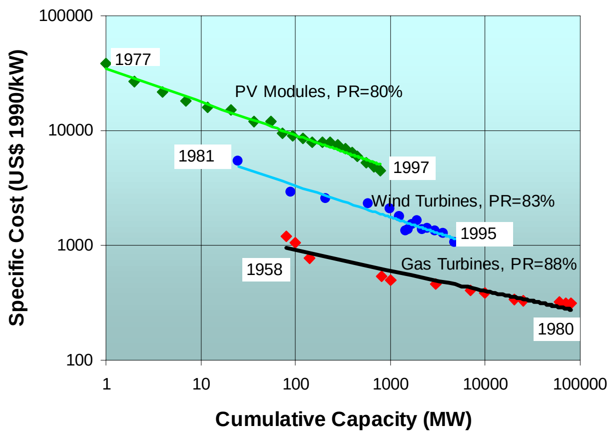
Examples of Learning Curves



Sources: Gas Turbines: Mac Gregor et al. (1991), IIASA-WEC (1995)
Wind Turbines, PV Modules: CNRS-IEPE (2000)

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MARKAL - Basic Formulation

- Linear programming „bottom-up" energy systems model.
- Detailed representation of technologies
- Minimise total discounted system cost:

$$z = cX$$

- Subject to the set of constraints:

$$AX \leq b$$

X: Vector of investment and activity variables

Endogenous Costs-1

- Linear Program (LP)

$$c = cte, \qquad z = cX$$

- Nonlinear Program (NLP)

$$c = aC^{-b}, \qquad C_t = C_0 + \sum_{\tau=1}^{t} X_\tau$$

$$c = f(X) \Rightarrow z = f(X) * X$$

Endogenous Costs-2

- Using Cumulative Cost:

$$TC = \int_0^C aC^{-b} * dC = \frac{a}{1-b} C^{1-b}$$

$$cX_t = TC_t - TC_{t-1} = \frac{a\left(C^{-b}{}_t - C^{-b}{}_{t-1}\right)}{1-b} = f(X)$$

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MIP - Interpolation Procedure

- Cumulative Capacity $C_{k,t} = C_{k,0} + \sum_{\tau=1}^{t} INV_{k,\tau} = \sum_{i=1}^{N} \lambda_{k,i,t}$
- Cumulative Cost $TC_{k,t} = \sum_{i=1}^{N} \alpha_{i,k} * \delta_{k,i,t} + \beta_{i,k} * \lambda_{k,i,t}$

$$\delta_{k,i,t} \in \{0,1\}$$

- Logical Constraints

$$\sum_{i=1}^{N} \delta_{k,i,t} = 1$$

$$\lambda_{k,i,t} \geq C_{i,k} * \delta_{k,i,t}$$

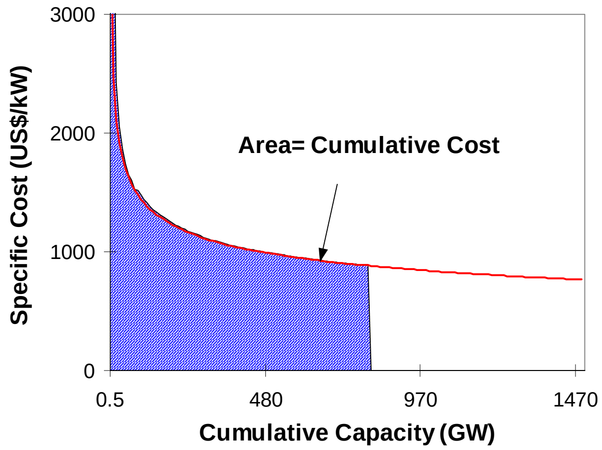
$$\lambda_{k,i,t} \leq C_{i+1,k} * \delta_{k,i,t}$$

MIP - Key Parameters

- Maximum Cumulative Capacity: $C_{k,max}$ is upper bound for the technology capacity
- Number of Segments N: Accuracy of representation Vs Computing Time
- Segmentation Procedure: Variable length segments. Shorter segments for fast decreasing zone of the curve
- Starting Point: Very sensitive. Problem for new or future technologies

Cumulative Cost

$$TC = \int_0^C aC^{-b} * dC = \frac{a}{1-b} C^{1-b}$$



Piecewise Cumulative Cost

- Expressed as a combination of linear segments: $TC_{k,t} = \sum_{i=1}^{N} \alpha_{i,k} * \delta_{k,i,t} + \beta_{i,k} * \lambda_{k,i,t}$
- Binary Variables: $\delta_{k,i,t} \in \{0,1\}$
- Slope of linear segment: $\beta_{i,k} = \dfrac{TC_{i,k} - TC_{i-1,k}}{C_{i,k} - C_{i-1,k}}$
- Intercept: $\alpha_{i,k} = TC_{i-1,k} - \beta_{i,k} C_{i-1,k}$

Objective Function

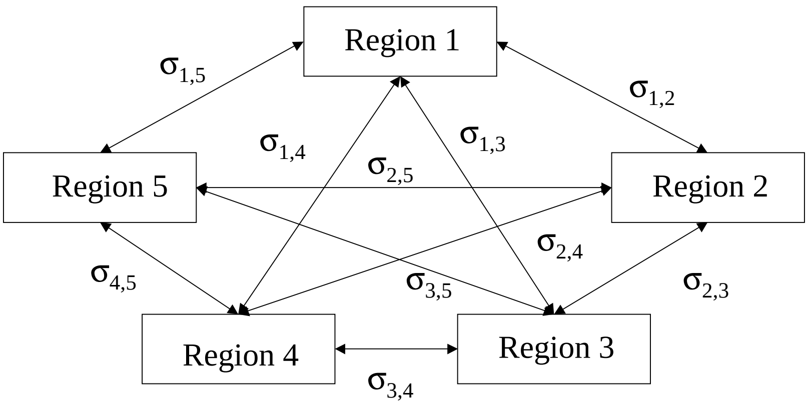
- Investment cost for a learning technology k in the time period t:

$$IC_{k,t} = TC_{k,t} - TC_{k,t-1}$$

- Objective function includes discounted investments for learning technologies:

$$z' = z_{NL} + \sum_{k \in L} \sum_{t=1}^{T} discfactor_t * IC_{k,t}$$

Multi-regional Learning Spillovers



$\sigma_{i,j}$: Spillover coefficients

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