The diffusion of photovoltaic energy across countries: modelling choices and forecasts for national growth patterns

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*joint work with Cinzia Mortarino
Introduction

- Marchetti (1979): “Society as a Learning System”. Diffusion of new energy sources and technological innovations related are co-evolutionary processes.

- Energy sources may be treated as products to be accepted by social systems!

- Use of innovation diffusion theory and models: Bass models (BM, GBM)


Photovoltaic solar energy

- Attractive alternative to fossil fuels
- Directly converts sun into electricity
- Use in on-grid and off-grid systems
- Meeting energy needs of people currently lacking electricity
- Disadvantages due to initial plant costs
- Adoption of a PV system: complex decision process
- Negative short-term outcomes in terms of financial investments and administrative procedures
Adoption and diffusion

- The success of a technology in a society ultimately depends on consumers accepting it.

- Bass models (BM, GBM): consumers are the driver of diffusion. Rationale for preferring them to other S-shaped models.

- Cross-country analysis of PV diffusion: differences in growth patterns and in incentive measures to stimulate internal demand. Institutional commitment is crucial in this context.
The Bass model

\[ z'(t) = (p + q \frac{z(t)}{m}) (m - z(t)) \]

- Innovators
- Imitators
- Market potential (carrying capacity)
- Cumulative adoptions
The Bass model

Closed form solution

\[ z(t) = m \frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p} e^{-(p+q)t}} \]

acts as scale parameter of the diffusion process

dynamics of diffusion in terms of parameters \( p \) and \( q \)
The Bass model

Parametric origin

\[ z(t) = m \frac{1 - e^{-(p+q)(t+d)}}{1 + \frac{q}{p} e^{-(p+q)(t+d)}} \]

d: unknown translation parameter to be estimated when information about initial stages of diffusion is not available
The Generalized Bass model

\[ z'(t) = (p + q \frac{z(t)}{m}) (m - z(t))x(t) \]

External intervention function.
Anticipates or delays adoptions. Does not modify the diffusion parameters.
May be used to identify the effect of incentive measures, political regulations, and other external factors. In BM \( x(t) = 1 \).
GBM: how to model \( x(t) \)

Exponential shock:
may be used to model the effect of
a drastic perturbation

\[
x(t) = 1 + ce^{b(t-a)}l_{t \geq a}
\]

c: represents depth and sign of intervention
b: describes persistence of the effect and in negative if the memory is decaying to the stationary position
a: represents the starting time of intervention
l: indicator function of event \((t>a)\)
GBM: how to model $x(t)$

Rectangular shock:
may be used to model
a more stable effect, acting for a relatively long period

\[ x(t) = 1 + c I_{t \geq a} I_{t \leq b} \]

$c$: represents depth and sign of intervention
$a-b$: temporal interval in which intervention occurs
$I$: indicator function of events ($t>a$) and ($t<b$)
The data

- International Energy Agency (IEA), 1992-2006
- Yearly installed cumulative power (in MW)
- No distinction between on-grid and off-grid
- Brevity of data series: uncertainties in forecasting
- Current growth of PV sector requires a specific effort to describe market evolution
Japan

BM with parametric origin
$R^2=0.999864$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>Standard Error</th>
<th>Confidence Interval</th>
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</table>
Japan

- R&D expenditure increased starting in 1979/1980
- Previous experience in PV cells for small devices (calculators and watches)
- 1992: New Sunshine Program
- 1994: “70.000 Roofs”, commonly perceived as the most effective
- But the GBM does not show a real improvement with respect to BM: $P^2=0.399015, F = 1.327869$
Germany

GBM with exponential shock
$R^2=0.999951$

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Germany

- Years 1990-1991: Electricity Feed in Law
- 2000: Renewable Energy Sources Act (EEG)
- Important adjustment in 2004, commonly considered cause of the acceleration. The model shows that such acceleration begun in 2003
- Peak of installations: 2006

IEA data for the period 1992-2007: modifications for the period 2004-2007. This implies some change in forecasting (shift of peak of about two years)
Australia

GBM with exponential shock and parametric origin
\( R^2 = 0.999911 \)

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Australia

- **Use of parametric origin**: origin significantly precedes 1992

- Exponential shock to identify fast growth followed by a slowdown, begun in 1998. No incentive measures.

- Possible interpretation of this behaviour in off-grid installations (isolated areas). **Two-phase diffusion**: initial demand by off-grid users.

- Still growing market: unstable estimate of m
France

GBM with rectangular shock and parametric origin
$R^2 = 0.999742$

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France

- Use of parametric origin because the process seems to have begun before 1992
- Negative perturbation from 1997 to 2004/2005: network externalities
- 13.03.2002: introduction of incentive measures
- The actions taken in the last two years cannot be evaluated through the data available but seem to support our forecasts about a growing trend for the next years
Netherlands

GBM with rectangular shock and parametric origin

$R^2=0.998947$

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Netherlands

- Installed PV capacity has clearly overtaken the peak: stable estimate of m
- Positive shock starting in 2002/2003: acceleration of adoption process
- Dutch government’s decision to end Energy Premium Regulation: race of new installations
- To realize the short-term Kyoto targets the Dutch energy policy excluded PV
- R&D investment: industrial development and implementation in the longer term
Concluding remarks

• The GBM is essential to account for the effect of exogenous interventions, like incentive policies.

• Fragile role of innovators (parameter p). Final decision does not rely just on final consumers: institutional commitment.

• Forecasts prospect a decline in various countries: is it a surprising result?

• But forecasts just apply to the technology currently in commerce, based on purified polysilicon.

• As new technologies are emerging an open question is whether waiting for a new generation of PV systems could reduce the disadvantage of the laggards.
Innovation diffusion modelling: some references


