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

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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)
- Guseo R., Dalla Valle A., Guidolin M. (2007) World Oil Depletion Models: Price Effects compared with strategic and technological interventions, Technological Forecasting and Social Change, 74 (4), 452-469
- Guidolin M., Mortarino C. (2010) Cross-country diffusion of photovoltaic systems: modelling choices and forecasts for national adoption patterns, Technological Forecasting and Social Change, 77 (2), 279-296

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

Market potential (carrying capacity)

$$z'(t) = \left(p + q\frac{z(t)}{m}\right)(m - z(t))$$

Innovators

Imitators

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

$$z'(t) = \left(p + q\frac{z(t)}{m}\right)(m - z(t))x(t)$$

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

$$x(t) = 1 + ce^{b(t-a)} I_{t \geq a}$$

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
I: 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

$$x(t) = 1 + cI_{t \geq a} I_{t \leq b}$$

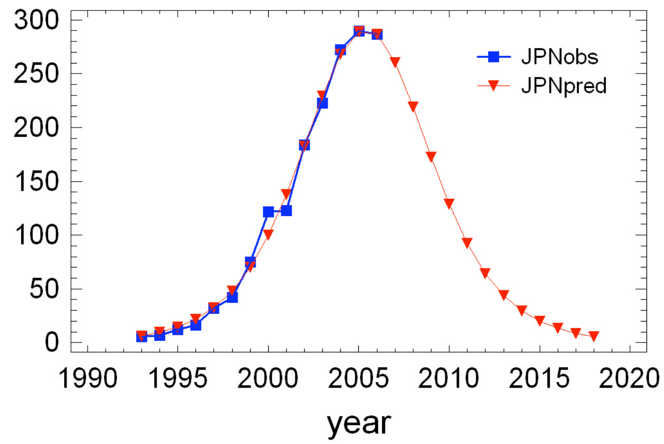
c: represents depth and sign of intervention
a-b: temporal interval in which intervention occurs
I: indicator function of events (t>a) and (t<b)

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



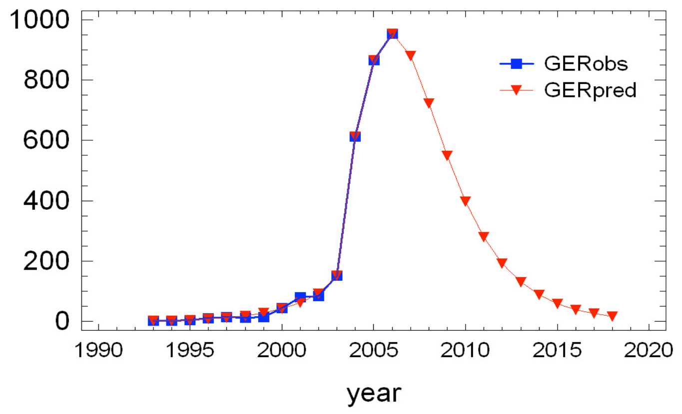
Parameter	Estimate	Standard Error	Confidence Interval	
			Lower	Upper
m	2777.69	114.991000	2524.600000	3030.790000
p	0.000123	0.000355	-0.000658	0.000904
q	0.420644	0.007624	0.403864	0.437424
d	5.459080	6.97595	-9.894920	20.813100

Japan

- R&D expenditure increased starting in1979/1980
- 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



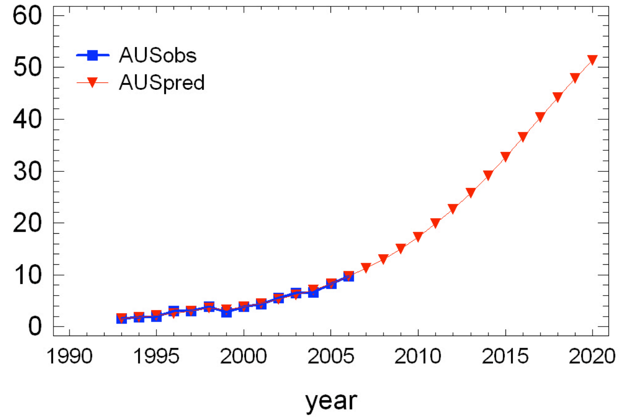
Parameter	Estimate	Standard Error	Confidence Interval	
			Lower	Upper
m	6276.50000	984.967000	4048.34000	8504.650000
p	0.000202	0.000046	0.000099	0.000305
q	0.415379	0.018583	0.373341	0.457417
c	1.765300	0.164350	1.393510	2.137080
b	-0.448399	0.136758	-0.757769	-0.139029
a	11.942100	0.086185	11.747200	12.137100

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

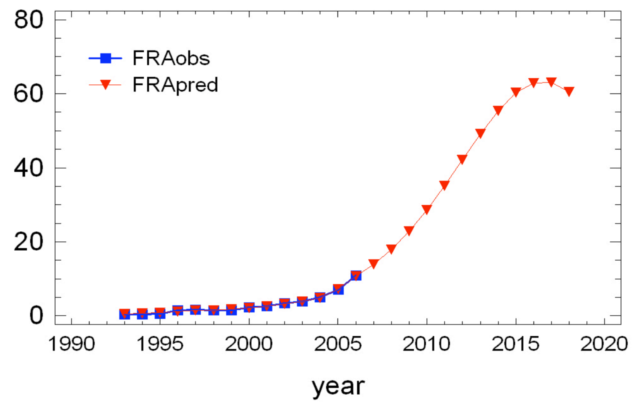


Parameter	Estimate	Standard Error	Confidence Interval	
			Lower	Upper
m	1449.690000	2214.50000	-3656.97000	6556.35000
p	0.000165	0.000157	-0.000197	0.000528
q	0.168429	0.011983	0.140796	0.196062
d	9.771120	3.015490	2.817370	16.724900
c	-0.230408	0.907092	-2.322170	1.861360
b	-0.111230	0.575294	-1.437860	1.215400
a	6.970450	0.154218	6.614830	7.326080

Australia

- Use of parametric origin: origin significantly precedes 1992
- Exponential shock to identify fast growth followed by a slowdown, begun in1998. 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

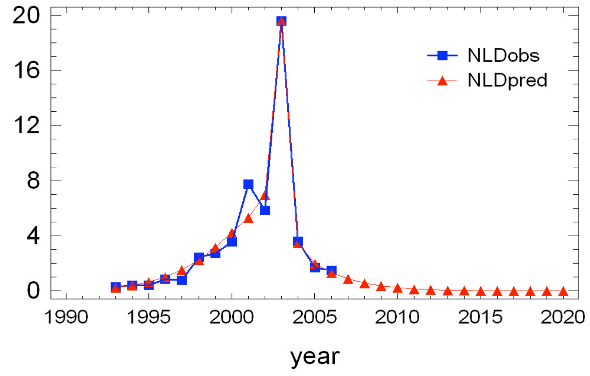
Parameter	Estimate	Standard Error	Confidence Interval	
			Lower	Upper
m	868.768000	5565.870000	-11966.20000	13703.70000
p	0.000047	0.000098	-0.000180	0.000274
q	0.292069	0.093498	0.076463	0.507676
d	6.962800	19.778600	-38.646900	52.572500
c	-0.282780	0.099794	-0.512907	-0.052653
a	6.000420	0.621072	4.568220	7.432620
b	13.498200	0.205912	13.023400	13.973000

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



Parameter	Estimate	Standard Error	Confidence Interval	
			Lower	Upper
m	55.138400	2.155930	50.166800	60.110000
p	0.000091	0.010314	-0.023693	0.023875
q	0.459654	0.279202	-0.184188	1.103500
d	7.198560	235.284000	-535.369000	549.766000
c	2.684290	0.571306	1.366860	4.001730
a	10.945500	0.204942	10.472900	11.418100
b	12.071500	0.225310	11.551900	12.591100

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

- Guidolin, M., Mortarino, C. (2010). Cross-country diffusion of photovoltaic systems: modellling choices and forecasts for national adoption patterns, Technological Forecasting and Social Change, 77 (2), 279-296
- Guseo, R., Guidolin, M. (2009). Modelling a Dynamic Market Potential: A Class of Automata Networks for Diffusion of Innovations, Technological Forecasting and Social Change, 76 (6), 806-820
- Guseo, R., Guidolin, M. (2008). Cellular Automata and Riccati Equation Models for Diffusion of Innovations. Statistical Methods and Applications, 17 (3), 291-308
- Guseo R., Dalla Valle A., Guidolin M. (2007) World Oil Depletion Models: Price Effects compared with strategic and technological interventions, Technological Forecasting and Social Change, 74 (4), 452-469