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A model for global and Australian electricity generation technology learning

Hayward, J. A.[1] **and P. W. Graham**[1]

[1]*Commonwealth Scientific and Industrial Research Organisation (CSIRO), Energy Technology Division,*
P.O. Box 330, Newcastle, NSW 2300, Australia
Email: jenny.hayward@csiro.au

Abstract: Various economic models have been applied recently to examine Australia's future energy mix based on projected cost and performance characteristics of emerging electricity generation technologies in the context of greenhouse gas emissions reduction. While these models do take into account the reduction in the cost of a new energy technology that occurs due to "learning-by-doing" or "learning-by-experience", the rates of "learning" used in the one-factor experience curves are based on a small number of international studies.

This paper discusses the development of an Australian model for technology uptake. It is also based on the robust one-factor learning curve. However, the difference with this model is that experience curves are placed into a three-region Australian and global economic model of electricity generation where the learning achieved by emerging technologies is a function of both global and local deployment of the technology, so called "compound learning". Wind energy has been taken as a case example, where an international experience curve was developed for wind turbines and local experience curves were developed for installation costs. When further data is obtained, this compound treatment of learning will be applied to all technologies where a local learning component can be justified.

In recent years the price of some electricity generation technologies has been increasing, most notably so for wind turbines and their installation. This price increase was not factored into the experience curves as it is assumed to be the result of market forces such as high demand for some types of power plant, profit-making and materials shortages and therefore separate from the phenomenon of learning. Rather the price increase has been interpreted as a "penalty" or price premium that entered the market once demand for wind turbines and their installation exceeded the capacity of wind turbine manufacturers. This penalty has been represented in the model as an additional payment to energy technology suppliers when investment in wind and other technologies is high relative to the total size of the power plant market.

The compound experience curves for wind provided a more realistic outlook for wind plant investment and deployment in Australia and globally. The penalty constraint was successful in preventing large, sudden increases in new capacity additions for wind and other learning technologies. When large additions were made, it increased the capital cost, in line with recent capital cost increases. The resultant global generation mix was varied and increased steadily with demand for low emissions technologies. The effect of the penalty on the Australian electricity generation technology mix is that wind still dominates new low emission electricity generation in the next two decades given its relative maturity to other low emission power sources. However, the higher penalty for rapid expansion of wind power has meant that other low emission source such as concentrating solar thermal power commence their deployment sooner than would otherwise be projected. Another effect of the penalty is that wind is less dominant in the long term where black coal-fired power stations with carbon capture and storage, hot fractured rocks, solar photovoltaic and concentrating solar thermal power plants are the largest sources of electricity generation.

Keywords: *Economic model, learning curve, experience curve, electricity generation technology*

1. MODELS OF TECHNOLOGY LEARNING

The phenomenon of “technology learning” has been observed for the development of new technologies and processes since mid last century (Wright, 1936; Alchian, 1949; Hirsch, 1956; Arrow, 1962; Dutton and Thomas, 1984; Grübler et al., 1999; Schrattenholzer and McDonald, 2001; Wene, 2007). Learning is typically represented in the form of a single-factor “experience curve”, where unit costs of a technology or process decrease by a certain percentage for every doubling of cumulative capacity or output i.e.

$$IC\ (CC) = IC(CC_0)*CC^{-b} \tag{1}$$

where IC(CC) is the investment cost of a technology at CC cumulative capacity, $IC(CC_0)$ is the investment cost at CC_0 unit cumulative capacity, and b is the learning index. The learning index is related to the learning rate LR by: $LR = 100 - 2^{-b}$ where LR is represented as a percentage.

Whilst single-factor experience curves for predicting future cost reductions may be considered an improvement on other approaches, increasing learning, knowledge and experience are not the only factors that reduce cost. The additional factors may be quite complex and can vary between technologies and even producers of the same commodity within the same factory (Dutton and Thomas, 1984; Alberth, 2008). Nevertheless, four broad factors have been identified by the International Energy Agency (IEA) (2000) that influence the slope of experience curves but may not be the result of learning about the technology.

Breakthroughs and positive changes in a technology (“technology structural change”) lead to a sharp decrease in the experience curve and the learning rate increases. “Market shakeout” occurs when price instead of cost data is used and results in a sharp increase in the learning rate. This can be observed after the early technological development stages when more competitors enter the market and the “Price Umbrella” the original manufacturers held “closes” and the price reflects the cost (Staff of the Boston Consulting Group, 1968). Nemet (2006) noted that this can also result in effects of economies of scale.

Experience curves can be a “compound system” i.e. a conglomerate of experience curves for different and interacting parts of the technology. For example, photovoltaic (PV) installations consist of PV modules and balance of systems (BOS). These two parts are reported to have quite different learning rates. The modules are part of an international market while the BOS are sourced locally (Shum and Watanabe, 2008; International Energy Agency, 2000; Junginger et al., 2005).

Experience curves calculated for energy technologies using national data often do not consider the source of the technology and this can result in a higher learning rate, as all the learning has happened elsewhere and yet the importing country benefits from the lower price (Junginger et al., 2005). This is also known as knowledge transfer or “spillover” (Grübler et al., 1999; Barreto and Kemp, 2008). “Government policy” in the form of R&D spending starts the learning process and accumulation of knowledge and experience, leading to demonstration projects for viable technologies. Governments can also influence the choice of technology, for example through mandates for a percentage of renewable energy by a given date, emissions trading schemes, feed-in tariffs and tax concessions.

2. AUSTRALIAN ELECTRICITY MODELS

Various models of electricity generation in Australia have been developed incorporating technology cost projections. However international estimates of learning rates are used and may not be as applicable in a local setting. International rates are based on international cumulative capacity and, since Australia’s cumulative capacity is much lower, Australia’s incremental additions to global capacity would generate small changes in costs. Alternatively, estimating experience curves specifically for Australian cumulative capacity and costs would not be accurate since most technological components are imported and are thus better explained by global developments. Applying international prices to changes in Australian cumulative capacity alone would lead to the erroneous conclusion that much faster learning is possible in Australia than internationally (Junginger et al., 2005).

To avoid these methodological errors, this paper calculates two types of experience curves (international and local) applied to wind energy technology as a case example. It is the intention of the authors to extend this methodology to other learning technologies where local learning can be justified and when further technology specific information is obtained.

3. GLOBAL AND LOCAL LEARNING MODEL (GALLM) METHODOLOGY

The mixed-integer objective function and some constraints are based on an adaptation of the ERIS model by Kypreos et al., (2000). The model contains three regions: Australia, other developed countries and developing countries. Technology learning is endogenous and treated on an international basis (a function of the activity in all three regions). However, wind features “compound learning” where the turbine learning is international and the BOS and installation are local. Black and brown coal pulverised fuel (pf) steam turbines, gas single cycle turbines, hydroelectricity, and nuclear power have no learning, instead they have a fixed capital cost.

The learning rates estimates are from Graham et al. (2008) CSIRO’s Energy Sector Model (ESM) except for wind. The wind turbine experience curve was calculated from IEA (2009) data as shown in Figure 1. While recently turbines have increasingly been installed in non-IEA countries, prices are difficult to obtain and may be significantly lower. Cyranoski (2009) found that these turbines have reliability issues, higher operating and maintenance (O&M) costs, and lower capacity factors. The regional installation experience curves were calculated from IEA data for the global region (Figure 1) and Australian data for Australia (Figure 2). Each data point represents a calendar year. Unfortunately, Australian data was not available for the year 2004.

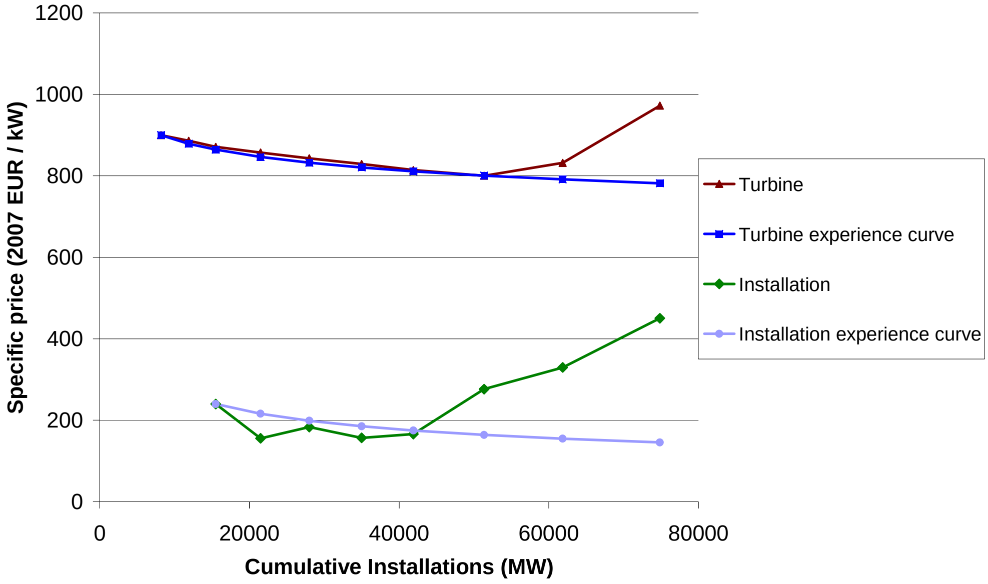

Figure 1. International turbine and experience curves

The prices of wind turbines and installation have been on the increase in recent years. Milborrow (2008) found that this was due to factors outside of the technology performance such as the global demand for raw materials, higher oil prices, high demand for wind turbines, skilled labour shortages, and profit. The price increase was not factored into the experience curves. Rather it is assumed to be a separate phenomenon from learning requiring a different approach. In our approach we interpret the price increase as a ‘penalty’ or price premium that entered the market once demand for wind turbines and their installation exceeded the capacity of wind turbine manufacturers and installers. This penalty has been represented in GALLM as an additional payment to technology suppliers when investment in wind and other technologies is high relative to the total size of the power plant market.

Another important constraint on learning technologies included in GALLM is that some technologies are defined to only be commercially available from a given point in time. Furthermore, all technologies have constraints placed on their technical potential (e.g. due to resource constraints), which in most cases exceeds installed capacity and so is often not binding. Australian government policies have been added. International policies are less comprehensively represented due to the high aggregation of the model. However, for wind energy, the wind incentive schemes have been included in an aggregated sense as a proxy for the individual country policies (Johns, 2008; World Wind Energy Association, 2009; Aubrey, 2008).

ESM is a partial equilibrium model of Australian electricity and transport sectors. To take advantage of the detailed state level policies, energy resource costs functions and other information in ESM it has been interfaced with GALLM to provide the technology uptake projections for Australia. The changes in capital costs over time from GALLM are exogenously fed into ESM and levels of technology uptake in Australia are generated. The ESM Australian installed capacities are then fed into GALLM and new technology capital cost projections for Australia are calculated. The process was repeated only twice to achieve convergence. The ESM-generated levels of uptake have little influence on the GALLM global results since the Australian market is small compared to the international market.

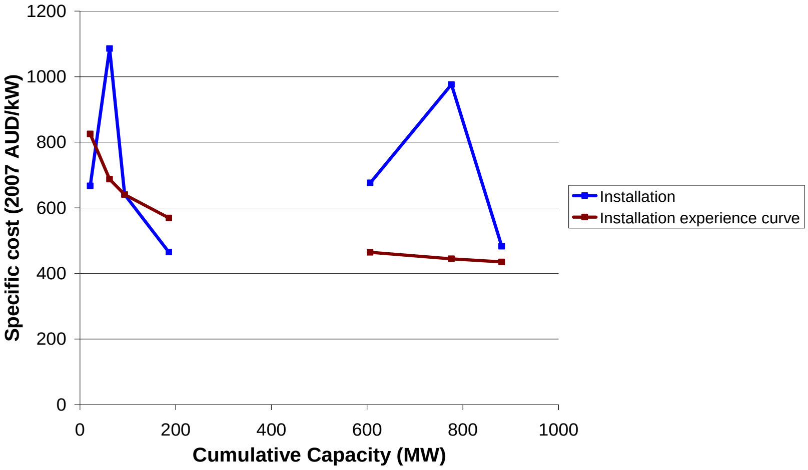

Figure 2. Australian installation experience curve

In the future additional constraints will be incorporated into the methodology to increase the robustness of GALLM. This might include incorporation of "technology structural changes" to take into account significant changes in a technology category which makes it lower cost in a relatively short time frame. Demand will also become elastic in GALLM to better interface with ESM and reflect the fact that global electricity demand is expected to decrease under future scenarios that include global emissions trading schemes.

4. GALLM/ESM VIEW OF FUTURE ELECTRICITY GENERATION

Electricity generated by technology in Australia and internationally is shown in Figure 3 and Figure 4 respectively.

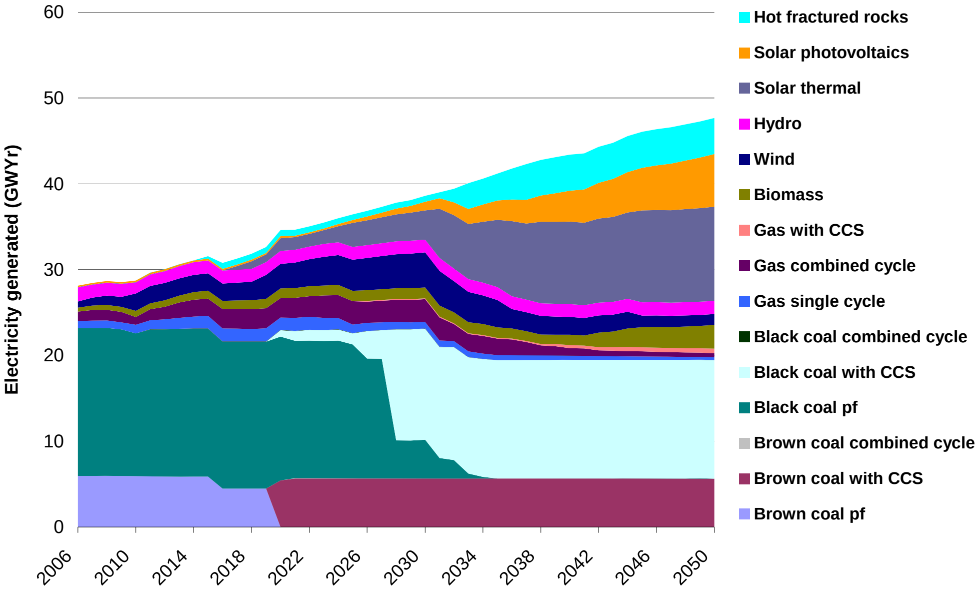

Figure 3. Australian electricity generation

A global carbon price scenario called CPRS-5 was introduced based on the Australian Government Department of Treasury estimates from the Carbon Pollution Reduction Scheme (CPRS) which is planned to introduce emission trading in Australia in 2010 (Commonwealth of Australia, 2008). The CPRS-5 also includes assumptions about other countries taking coordinated action and the carbon price that would be required over time.

Australia's current main source of generation is brown and black coal pulverised fuel (pf) steam turbines. The effect of the penalty on the Australian electricity generation technology mix is that wind still dominates new low emission electricity generation in the next two decades given its relative maturity to other low emission power sources. However, the higher penalty for rapid expansion of wind power has meant that other low emission source such as solar thermal commence their deployment sooner than would otherwise be projected. Another effect of the penalty is that wind is less dominant in the long term where black coal-fired power stations with carbon capture and storage (CCS), hot fractured rocks, solar photovoltaic and solar thermal power plants are the largest sources of electricity generation.

Solar thermal's large contribution in part also reflects its relatively high learning rate (15%) and high global uptake. It is also the least constrained in terms of resources compared to hot fractured rocks, which has the same high learning rate. Also note that the early uptake of black or brown coal-fired power with CCS is constrained in the model to not occur before 2020 because it is assumed the technology will not be commercially available before that time.

Globally, the picture is more diverse with no single low-emission technology clearly dominant once the CPRS-5 carbon price is introduced (which is in 2010 for developed countries and 2025 for the developing world).

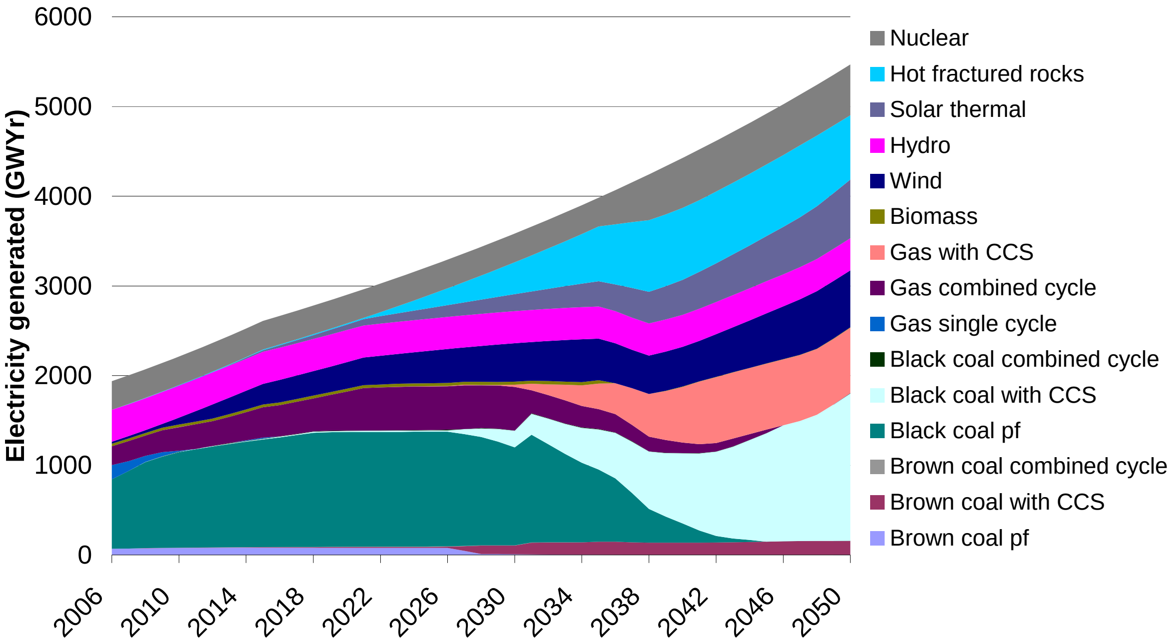

Figure 4. Global electricity generation

5. THE EFFECT OF THE PENALTY CONSTRAINT

The high penalty constraint placed on wind installations affected the capital cost of wind, as can be seen in Figure 5, where there was a sharp increase in the cost between the years 2008 and 2015 when a high amount of wind was installed. Note that installations were fixed for the developed world in the years 2006-2008 as the actual installations are known.

In later years of the model the penalty resulted in a gradual introduction of wind into the generation mix, as can be seen in Figure 6, with the striking difference in new capacity additions in the model with and without the penalty constraint. When the penalty is not enforced wind is added in huge blocks which would not be realistic for a wind turbine industry and has not been the case in the past. With the penalty in place, wind is installed at a more moderate rate.

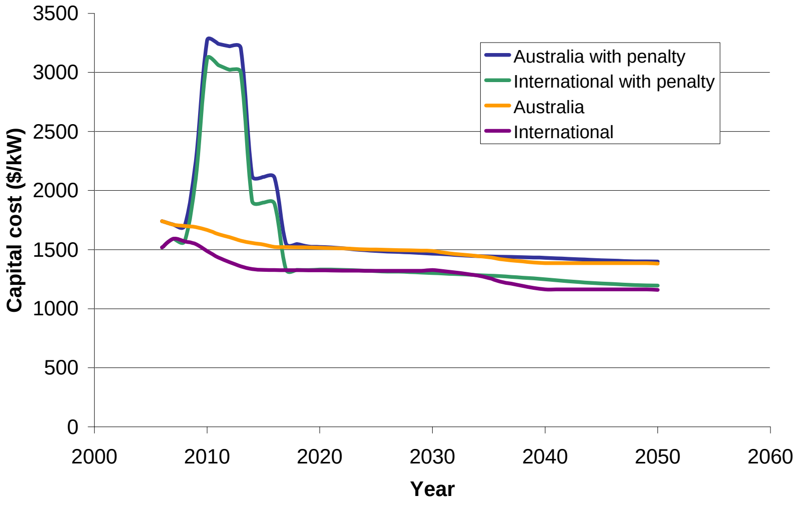

Figure 5. Australian and global capital cost for wind

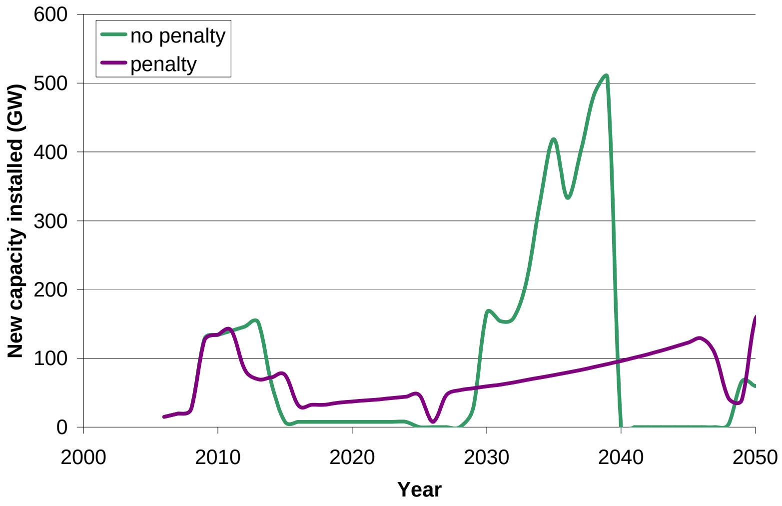

Figure 6. Global wind new capacity additions with and without the penalty.

6. CONCLUSION

The paper presented a methodology for endogenously projecting technological change based on both local and global technology learning and incorporation of a penalty function to take into account the effect of market forces and profit taking on technology prices. Using this approach, GALLM’s predicted global electricity generation mix is varied and increases steadily for low emissions technologies. By combining GALLM with ESM, the Australian electricity generation technology capital cost projections are internationally-consistent, with the added benefit of local costs for installation of wind, but they also factor in the detailed state and federal Australian government policies and resource constraints that will influence the outcome for technology uptake. The resultant Australian technology mix was varied however, after 2030 black coal-fired power stations with CCS and concentrating solar thermal electricity generation tended to dominate more than was observed globally.

The compound experience curves for wind provided a realistic outlook for future wind electricity generation in Australia and globally. The penalty constraint was successful in preventing large, sudden increases in new capacity additions for wind. When large additions were made, it increased the capital cost, in line with recent experience of capital cost increases in wind turbines and installations.

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