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A global and local endogenous experience curve model for projecting future uptake and cost of electricity generation technologies

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ABSTRACT

A global and local learning model (GALLM) has been developed to project the cost and global uptake of different electricity generation technologies to the year 2050. This model features three regions, endogenous technological learning within and across those regions, various government policies to facilitate technological learning and a penalty constraint which is used to mimic the effect market forces play on the capital cost of electricity generation technologies. This constraint has been added as market forces have been a strong factor in technology pricing in recent years. Global, regional and component experience curves have been developed for some technologies. The model, with the inclusion of these features, projects a diverse range of technologies contributing to global electricity generation under a carbon price scenario. The penalty constraint leads to gradual and continual installations of technologies and because the constraint provides a disincentive to install too much of a technology, it reduces the impact of uncertainty in the learning rate. Alternative forms of the penalty constraint were tested for their suitability; it was found that, with a zero and lower-cost version of the constraint, photovoltaics are installed in a boom-and-bust cycle, which is not supported by past experience. When the constraint is set at a high level, there are fewer installations.

1. Introduction

The study of quantifiable relationships explaining the phenomenon of technological change has a long history dating back to at least the beginning of last century when it was observed by Wright (1936) that the cost of producing military aircraft declined at a more or less constant rate for each doubling of aircraft produced. At present, the energy sector's focus on this subject is to be able to create projections of the future cost of electricity generation technologies. Of particular interest are lower greenhouse gas emission intensity technologies, which can be economically viable following the introduction of policies that will provide incentives to the sector to reduce emissions.

Various studies have been published recently to project the cost and performance characteristics of emerging electricity generation technologies in Australia (AU) in the context of greenhouse gas emissions reduction and associated government policies (for example, see (ACIL Tasman, 2009; CSIRO, 2011; EPRI Palo Alto CA and Commonwealth of Australia, 2010)). Whilst these studies partially adopt an experience curve approach, they do not explicitly model the co-dependency of uptake and cost reduction nor adequately separate local and global learning drivers when selecting learning rates (LR). The ultimate goal of this work has been to improve projections of the cost of electricity generation in AU, in particular the projected capital costs as capital cost contributes a large portion of most low emission technologies.

A combined global and local modelling framework is likely to be a much more accurate approach for determining capital costs for several reasons. International estimates of LR may not be valid in a local setting. International rates are based on international cumulative capacity and, since AU's cumulative capacity is much lower, AU's incremental additions to global capacity would generate small changes in costs. Alternatively, estimating experience curves specifically for AU cumulative capacity and costs would not be appropriate since most technological components are imported and are thus better explained by global developments. Applying international prices to changes in AU cumulative capacity alone would lead to the erroneous conclusion that much faster learning is possible in AU than internationally (Junginger et al., 2005).

Another concern with previous Australian studies is whether they have considered the multiple factors that affect technology prices other than technological improvement. The capital cost of any particular electricity generation technology can be influenced by many factors, and when price data is used to generate experience cost curves this can influence the shape and LR observed. For instance, exchange rates and commodity prices fluctuate and this can affect the cost of materials used in plant construction or the cost of specific imported components. Regional variations in labour rates and productivities can be a factor in

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technologies which require a great deal of labour-intensive construction (e.g. coal-fired and nuclear power stations) (BREE, 2012; van Sark et al., 2010). Economies of scale have an effect, where it has been shown that plant built on a larger scale tends to have a lower per unit cost (Peters et al., 2003); economies of scale in manufacturing can also reduce costs (Qiu and Anadon, 2012). Governments, by providing subsidies, grants, sponsoring R&D or incentive programmes such as carbon pricing can influence the capital cost by helping with the deployment of new technologies via "market-push" and "demand-pull" (Nemet, 2009), which increases learning and experience and thus assists with moving these technologies down the experience curve. Market forces in the form of resource and production constraints have been in some cases the strongest determinant of changes in technology prices. As such, a methodology would be required to capture this important factor.

With these considerations in mind the Commonwealth Scientific and Industrial Research Organisation (CSIRO) developed a quantitative model — the Global and Local Learning Model (GALLM), based on the objective function and constraints of the ERIS model developed by Kypreos et al. (2000) but with the addition of several new approaches to the study of technological change (Hayward et al., 2011). The model requires significant data inputs but not overly-detailed expert knowledge of each technology category. It has three regions, with global and local technological learning. It endogenously includes the effect of market forces on capital costs and technology uptake. It also includes various government policies and incentives to promote low-emissions technologies.

In this paper experience curves and four other drivers of changes in cost are firstly discussed. Examples of experience curves that were developed for GALLM are discussed, then how market forces and government policies were dealt with. Results from GALLM are provided including the effect the penalty constraint has on these results and the sensitivity of GALLM is shown. Conclusions then follow.

2. Experience curves

The phenomenon of "technology learning" has been observed for many years (Alchian, 1949; Hirsch, 1956; Wright, 1936). The term "learning-by-doing" was coined by Arrow (1962) and was used to explain the effect increasing the knowledge or experience of the labour force had on the economics of production of technology and processes (improvements in per capita income).

Grübler et al. (1999) discussed and demonstrated how technology learning and diffusion for energy technologies can be incorporated into economic models of electricity generation. Schrattenholzer and McDonald (2001) calculated experience curves and rates of learning for many energy-related technologies as, up until then, LR from other technologies were being used (Dutton and Thomas, 1984). Interestingly, the majority of LR were estimated to be approximately 20% for relatively new technologies. Wene (2007) later investigated the reasons for this using the theoretical construct of a non-trivial machine (NTM) of the process of technology learning. It was found that the following three LR can describe the phases of continuous feedback in the NTM technology learning system: 20%, 7% and 4%. In the literature, LR often differ by these values and there are several reasons why. These will be discussed below.

Technology learning is typically represented in the form of an "experience curve",[1] where unit costs of a technology or process decrease by a certain percentage (the LR) for every doubling of cumulative capacity or output i.e.

$$IC = IC_0 \times \left(\frac{CC}{CC_0}\right)^{-b} \tag{1}$$

where IC is the investment cost of a technology at CC cumulative capacity, IC_0 is the investment cost at CC_0 cumulative capacity, and b is the learning index. The learning index is related to LR by the following equation

$$LR = 100 \times \left(1 - 2^{-b}\right) \tag{2}$$

where LR is represented as a percentage of cost.

However, the validity of using the single factor experience curve for predicting future cost reductions has always been under question as the actual factors that lead to the cost reduction are not just from increasing learning, knowledge, economies of scale, experience or investments in a technology but may be quite complex and vary between technologies and even producers of the same commodity and/or within the same factory (Alberth, 2008; Dutton and Thomas, 1984; Sagar and van der Zwaan, 2006). Experience curves can only ever be determined for technologies that have actually been commercialised, as these have historical cost data. Therefore, there is some danger in using experience curves for early learning/emerging technologies as these technologies might never actually be available in the marketplace (Sagar and van der Zwaan, 2006). To provide a framework for understanding the various drivers, the International Energy Agency (2000) identified four broad factors that can influence the slope of an experience curve

- Positive changes in the technology, termed "technology structural changes" lead to a sharp decrease in the experience curve (increased rate of learning, thus sharp increase in b and resultant decrease in the investment cost IC) over a short period of cumulative capacity increase, where learning switches from one curve (or rate of learning) to another.
- Market shakeout, which happens when price is observed instead of cost, can also result in a sharp increase in the LR. A shakeout can be observed after the early stages of the development of a technology. When more competitors enter the market, the price umbrella the original manufacturers held when they were exclusive suppliers is lost and the price returns closer to the marginal cost curve cost (Staff of the Boston Consulting Group, 1968). This has little to do with learning since it may represent little or no change in costs. However, more often only price data is available and consequently this phenomenon can have a significant impact on construction and application of learning curves.
- Government policy and research, development and demonstration project spending can affect the slope of the realised learning curve by accelerating the learning process via accumulation of knowledge and experience. Policies can also influence the choice of technology, through mandates for a percentage of renewable energy by a given date, emissions trading schemes, feed-in tariffs, tax concessions etc. (Nemet, 2009).
- Finally, experience curves can be a compounded effect of experience curves for different and interacting parts of a system. For example, photovoltaic (PV) installations are made up of PV modules and balance of systems (BOS) which includes the inverter. These are reported to have quite different LR and may be sourced globally (module) whilst the BOS is local (International Energy Agency, 2000; Junginger et al., 2005; Shum and Watanabe, 2008). The existence of compound effects also means that separate technologies with common components can experience learning even if not deployed, as long as one technology with the shared component is deployed.

Before the approach applied in GALLM is discussed, four types of important sources of "learning" are discussed below.

2.1. Local versus global learning

Experience curves calculated for energy technologies using national or local cumulative capacities and costs often do not consider the source

[1] Experience curves are also commonly known as learning curves. This paper uses the term experience curve as defined in International Energy Agency (2000).