Wave Energy Technology Development Review in the UK: Application of the Learning Curve Concept, 1970-1999

Wave Energy Technology Development Review in the UK: Application of the Learning Curve Concept, 1970-1999

Audrey Mukora, Henry Jeffrey, Mark Winskel & Markus Mueller

IES, School of Engineering and Electronics, Joint Research in Energy University of Edinburgh, UK
Tel: 0131 6513575, a.mukora@ed.ac.uk, mark.winskel@ed.ac.uk, markus.mueller@ed.ac.uk, henry.jeffrey@ed.ac.uk.

Introduction

Sustainable energy systems require policies that encourage development and deployment of alternative sources of electricity to help tackle the challenges of climate change and ensure electricity supplies. A number of early-stage supply technologies have the potential to make significant contribution to carbon emissions reduction in future energy mixes. Most of these sources emerging are generally technically feasible but fall short economically in comparison with conventional sources but have potential to reduce costs with innovation. This entails exploring new methods of analysing technical change and policy measures for implementing and promoting technical change. Learning curve concept is one such tool.

Learning curves are based on a model of innovation which emphasises deployment and continuity of policy support. The framework of innovation underpinning this tool accentuates the stimulation of gradual upscaling and incremental deployment. For early stage technologies this can be sustained by"niche" support which allowing learning by interacting and dissemination of data.

One of the emerging technologies with potential to help meet challenges facing the energy sector is wave energy. General research interest in wave energy in the UK began in the early 1970s in response to the oil crisis. This saw the establishment of R&D programs such as the government funded Wave Energy Program (WEP) The program was responsible for large scale R&D activities and technology progress assessments from the mid 1970s until the early 1980s. A significant amount of work was carried out but most of this is not well referenced and access to recorded information is limited. There is also general lack of awareness of this work amongst wave energy developers of today.

Taking the idea of learning curves, this paper reviews wave energy technology in the 1970s and 1980s. It analyses wave technology development and the methods that were used to assess cost reduction during this period with the aim of finding out to assess the relevance of the learning curve methodology for the learning wave energy program.

These WEP was essentially unsuccessful and this period was characterised by discontinuities in government support which inevitably affected technological progress. It is suggested that better appreciation of the learning curve tool could have reduced risks of failure programs. Lack of awareness of the dynamics of learning led to limited learning effects, in particular through pre-emptive up-scaling and discontinuity of funding. Much cost data had low levels of accuracy and could not be validated because of lack of operational experience Even though the programs were not a success and were carried out under a different environment from the present, the knowledge can have continuing impact on the development of wave energy in the future especially if all available information is made accessible and the stock of knowledge is utilised.

Learning Effects and Curves

Learning effects are based on the principle that costs reduce with experience gained. These represented on learning curves demonstrate that the input cost per unit produced decreases by a set percentage (learning rate) every time cumulative production output doubles. There has been a growing interest in the use of learning effects and learning curves in emerging energy technologies (Neij, 1997;

Junginger et al., 2006; Nemet, 2006). This also provides indications learning investments required to reach to situation of breakeven with conventional technologies (Alberth, 2007). Learning curves' simplicity and universality has led to their application in many areas. (Papineau, 2006).

The effect of R&D efforts on technology cost reduction is analogous to experience, in that it can bring about dynamic economies or downward shifts in the cost curve (Papineau, 2006). It is important to study the main mechanisms by which R&D investments contribute to cost performance. Assessing and quantifying the effects of R&D is usually difficult because of lack of data on research efforts and the broad range of R&D activities.

It is necessary to study learning effects for energy technologies. Climate change models and energy systems models now incorporate learning curves to endogenise technical change. Policy makers and investors require long term forecasts but data on their current and future performance is limited. With reliable data, learning curves can assist in providing information on the future role of emerging technologies. Public support, such as that in WEP creates an environment that allows interaction as opposed to the mainly private contemporary work.

Wave Energy General History

Formal interest in wave energy by the UK government through the Department of Energy (DEn) began in 1973. It was not a recent entrant to the energy scene. Between 1856 and 1973 over 340 patents for wave powered generation were granted. There was a general reduced interest between 1935 and 1970 and the resurgence in the early 1970s was caused by oil price increases (Leishman and Scobie, 1976).

A study in 1974 by the National Engineering Laboratory (NEL) recommended that the UK maintains an interest in wave energy production (Leishman and Scobie, 1976). In 1975 it was reported that there was no new source that appeared more attractive economically than wave (Ross, 1979). This marked the beginning of DEn's Wave Energy Program (WEP). The Energy Technology Support Unit (ETSU) based at Harwell was asked to formulate and manage WEP (Davies 1985). Through this program, the DEn funded extensive research between 1974 and 1983 costing approximately £15m in 1981 money (equivalent to £39.6m in 2006 money[1]) (Thorpe, 1992).

A Wave Energy Steering Committee (WESC) was set up to oversee as well as advise on the technical content of the program (Grove-Palmer, 1982; Davies, 1985). The Advisory Council on Research and Development for Fuel and Power (ACORD) was responsible for reviewing all renewable energy programs including WEP and making recommendations to the DEn. (Glendenning, 1977).

The WEP funding allowed work to be carried on collection and analysis of wave data, the study of wave forces on the devices, transmission and construction of wave tanks. High levels of wave energy resource in the sea had been reported and it was recorded that 80kW/m of wave front power approached Britain's Atlantic Coast.

At the beginning of the program 12 devices were chosen for analysis. To establish a common basis of assessment of devices under the program, device developer teams were asked to optimise their designs to meet the target of a 2 GW wave power station to be installed off South Uist in the Outer Hebrides. DEn's specialist consultants, Rendel, Palmer and Tritton (RPT) worked with the teams to assess the resulting station designs, making the reference design specifications (Davies, 1985).

The WEP estimated the cost of electricity generation for 4 of the devices in the range 20-50p/kWh (Grove-Palmer, 1982). This was a dramatic increase from earlier estimates because of capital costs increases, the realisation of less available power in the sea and lower load factors. ACORD reviewed the program in 1978 and 1979 and advised developer teams on the importance it attached to sea trial near full scale (Grove-Palmer,

[1] Converted using the GDP deflator used for fuel prices. See http://www.statistics.gov.uk for GDP statistics

1982). It also set an objective for device teams to reduce costs to 10p/kWh.

In March 1980 ACORD recommended that the number of devices being studied in the program be reduced to those most likely devices to go to sea trials. It set deadlines for March 1982 for prototype selection and for halving the cost from 10 to 5p/kWh. The teams prepared estimates and recommended 12 months work to finalise details of the prototype for sea trials. The focus was short term and this could have been a challenge for these developers most of whose designs involved novel ideas and untested ideas.

In 1982 ETSU appraised all UK renewable energy technologies for the DEn and it was concluded that there was a low probability of any design achieving an energy cost below 8p/kWh (ETSU, 1982). The overall economic assessment concluded that wave power was economic in those scenarios which favored renewable energy technologies, but only at its lowest predicted costs. ACORD concluded that large scale prototype work was not justified and DEn therefore decided to only fund a small scale program. This marked the end of significant government funding for wave energy

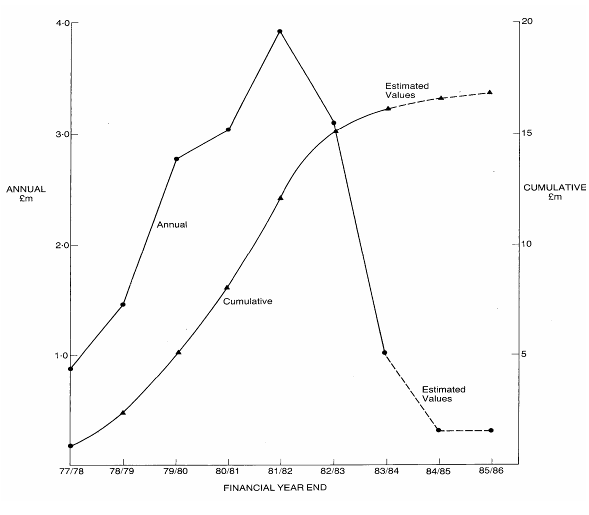

Fig 1: Annual and cumulative WEP expenditure (Davies, 1985)

Curves in Figure 1 are a representation of the annual and cumulative expenditure of the WEP from its inception to the point of discontinuity. The early days of WEP were marked with high government financial support which reached a peak around 1981 before a sudden fall. This is typical of many public funded programs and the wind energy program in the US in the 1970s is a typical example (Garud and Karnoe, 2003). With no design consensus amongst developers the WEP, it might have been a challenge forecasting on the future of this technology.

When the government's active support for wave energy funding was reduced; the technology was placed under "watching brief" and research was hit hard by the cut backs. An extensive review by ETSU headed by T W Thorpe concluded in 1992 that wave was unlikely to be competitive in the short to medium term (Thorpe, 1992). The "second closure" of wave energy R&D programs by the government was in 1994 (Ross, 2002). In 1999, the Government re-launched its wave energy R&D program on a much smaller scale to help assess the extent to which wave power could help meet energy needs (Thorpe, 1999).

Methods of assessment

The most frequently used method for comparing the economics of alternative wave energy conversion systems is to estimate the cost of electricity generation. This is typically expressed as the cost per unit electricity over a given time. Electricity production costs depend on the initial capital investment, running costs and the electricity output as well as the manner in which the project is financed.

Several WEP assessments were carried out between 1977 and 1982 by RPT, DEn consultants, who developed their own methods. The device teams also carried out their own assessments with the help of industrial specialist consultants in some cases. Technical assessments were qualitative, identifying areas of development and listing R&D requirements Economic assessments involved calculating the annual output and the annual costs.

The output was calculated from the resource, the device design performance and availability. Methods and models were formulated to calculate capital costs and O&M costs. Different approaches were taken depending on who was assessing. Combinations of engineering costing methods and statistical methodologies would be applied for the assessments. With no operational experience, most data in the early days was acquired analogously from similar projects in the offshore sector and other industries..

In the 1990s, ETSU carried out independent assessments for the DTI reported in 1992 and 1999 led by Tom Thorpe. Independent specialist consultants were contracted to develop models and methodologies for assessments under the guidance of the WESC. Notably, parametric costing, an approach more relevant to projects in early stage was used for capital costing. There was considerable dialogue with the device teams for transparency and consensus on the approaches taken and the resulting estimates (Dawson, 1979; Grove-Palmer, 1982; Thorpe and Marrow, 1989; Thorpe, 1991; Thorpe, 1992; Thorpe, 1992; Thorpe, 1999).

Case studies-

1. Edinburgh Duck offshore device

The Edinburgh Duck, a large scale device was designed with the aim of exploiting the maximum amount of energy resource available in deep water necessitating a long term R&D program. The Duck evolved from work instigated by Professor Salter at Edinburgh University and was incorporated into WEP in 1976 (Thorpe, 1991; Thorpe, 1992). It was largely a new design that had many novel components which was considered competitive if solutions were found for engineering problems presented by the design.

The team continuously improved their understanding of the device behavior and took advantage of engineering developments in other sectors. It contracted industrial consultants for their own costing. Novel mechanical components were priced by analogy of components of similar complexity in such as car engines. The team's estimate for the cost of electricity in 1979 at 5% interest was **5.5** p/kWh. As with other assessed devices there were significant differences between the team's values and the consultants'. For the Duck the consultants estimated the cost of electricity in the range **7.2**p/kWh to **8.2**p/kWh.

Table 1 shows the results for the Thorpe reviews. For the 1992 review, initially a rerun assessment was done for the design that had been reviewed at the end of WEP, the 1983 design.

Characteristics	**1983 Design**	**1991 Design**	**1998 Design**
Availability (%)	16.2	52.9	98
(GWh/year)	1,241	5,578	5,288
Capital Costs (£B)	6.3	5.6	2.4
(p/kWh) 8% DR	**57**	**17**	**5.3**
(p/kWh) 15% DR	**83**	**26**	**8**

Table 1: Comparison of Duck Designs (Thorpe, 1992; Thorpe, 1999)

The capital cost estimates in £B show that the 2GW scheme was a quite a large scale project for a relatively new technology. Capital costs can also be used to analyse cost reductions of the designs. This is also essential for prioritising R&D efforts and such information can be used for technology roadmapping. The figure 2 indicates cost reduction for the Duck as assessed by Thorpe in 1992 and 1999 (Thorpe, 1999).

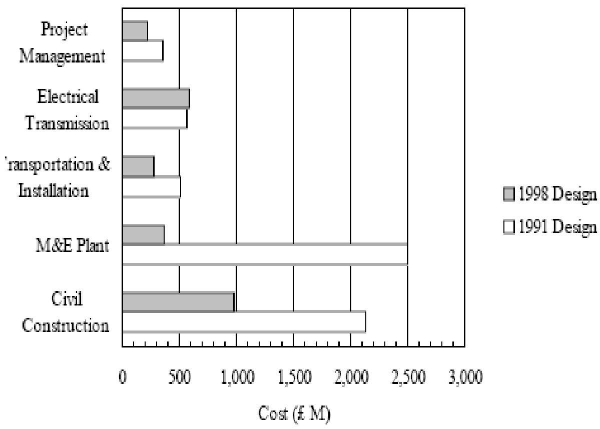

Fig 2: Capital cost breakdown for the Duck (Thorpe 1999)

2. Shoreline Devices- The Limpet

Earlier work on wave energy was on large devices but after the fall of the WEP focus shifted to smaller devices near or on the shoreline. The Limpet, a shoreline based OWC (Oscillating Water Column) device, was developed in the late 1990s by Queen's University of Belfast and Wavegen (formerly ART). It built on the experience gained on OWC development work by the university which began in 1985 [Thorpe, 1999]. An early OWC device, the 150KW Gully scheme, had been connected to the grid during the period 1989 to 1991

The Limpet was not yet finalised when it was assessed for the 1999 review. The device was site specific and capital costs were predicted in the range £850,000 to £1,160,000. Some of the data was commercially sensitive. The generating cost of Limpet was evaluated for a lifetime of 30years using different discount rates up to 15% giving costs between **3.5** and **10**p/kWh. The early OWC Gully concept had been estimated in the range **5** to **11** p/kWh.

The development of shoreline devices was improved by the experience gained from the earlier large scale devices and better understanding of the wave resource. Capital cost investments required were considerably lower than for the 2GW onshore scheme thus less project risk.

Discussion

There were efforts as early as the 1970s to find ways to reduce costs through improving designs of the energy converters and proposed methods of manufacture though R&D, for an example, a study in the 1970s on mass production of devices to realise cost reduction potential. There was an increase in knowledge of the technology as well as methods of energy capture and methods of assessment. This improved knowledge was a possible source of cost reduction. As there was no deployment, this did not result in cumulative power generation or increases in efficiencies necessarily.

The cessation of WEP funding may have been too premature (DEn, 1980; Grove-Palmer, 1982). Policy measures could have been put in place to complete all R&D activities to the point of deployment readiness first, unless there was sufficient informed evidence for abandoning the program. R&D efforts are capital intensive but can reduce costs to low levels in the long run. In 1982, the WEP manager concluded that work for the WEP was very close to reaching valuable results and work should have been continued until a prototype had been built (Grove-Palmer, 1982). Some critics argue that the process of convergence, choosing which technologies to focus on and which to ignore was carried out too early (Elliot, 1987)

When ACORD made a decision to cease the WEP in 1982, it provided funding to wind up the program and record findings so as to add value to any future work. It seems unclear if this objective was achieved as this work is not easily available. Private funding from the 1990s tended to go into financing new developments rather than developing the UK industry, resulting in the undermining of UK R&D efforts for new renewable energy technologies (Connor, 2003)

The results of assessments always carried caution on the accuracy of costs estimated for this immature technology. The accuracy of early WEP cost estimates could have been compromised by the methods of assessment. The estimates were only preliminary and were based upon assumptions that were yet to be substantiated through accumulation of appropriate data. The use of independent consultants in the Thorpe reviews improved the levels of accuracy but it was difficult to validate the results without commercial experience.

The value added to the development of the technology in the future from the account of the events that took place is dependent on available recorded information. There are suggestions that important information was not recorded in well-established source. For example, the 1994 closure of the wave energy R&D program is hardly documented. There were a number of areas of disagreement and this resulted in different approaches of recording accounts. Limited references available to validate information pose a challenge when reviewing work prior to 1999. There is a possibility that appraisal optimism was displayed by the teams. (Gross et al., 2007).

The 2GW design was too ambitious at the stage of development for the technology

(Connor, 2003). It had a short term political motive as the government was under pressure after the oil crisis in the early 1970s and the perceived large resource in the sea. The proposed rapid deployment allowed insufficient time for learning to take place. There was need to start small and then gain experience. The knowledge gained from the small scale was transferable and it was possible to develop and gain more experience from these as can be realised from the Limpet that was developed from the Natural Gully OWC and was deployed.

Conclusion

The development of wave energy technology in the UK from 1970 to 1999 was marked with discontinuities. The period to the 1980s was dominated by government funded and controlled R&D activities through the WEP and nationalised electricity markets. Cost reductions were recorded for wave energy devices in general but the program was not a success in that technology did not become competitive with other sources. There was continuous assessment of devices using but the estimates had low levels of accuracy and different approaches to assessments were used.

It is difficult to develop a credible learning curve for this period due to lack of learning by deployment but assumed learning by research. Though data was publicly available, it was inconsistent lacking robustness underpinning credible learning curves. The discontinuities inhibited incremental progress characterising learning by doing.

The technology was quite immature and there was no operational experience. The only learning that can be observed or implied is learning-by-research. As the idea of learning for emerging energy technologies is further developed and better understood, it might be possible to apply learning curves using cumulative R&D expenditure by way of the 2 factor learning curves. This requires further study of R&D activities and spending and resulting cost reductions directly attributed to this. This kind of information is not easily accessible and might not be available for the period studied.

The methods used for economic assessment can also have an impact on the application of leaning curves. The different methods used or environment in which this was executed would make it potentially misleading to compare such data and plot a curve to illustrate cost reduction. The only advantage of the data is that most of the work was publicly funded without commercial sensitivity.

Even though the WEP faced some criticism, there is much to learn from it. Positive results can be emulated and mistakes avoided. The importance of continuous assessment of devices using common methods should be emphasised. For technologies still in their early stages of development, the costs are not stable. The use of different comparative methods can assist in getting accurate estimates where operational experience does not exist. This should be done with moderation using validated and justified methods as too many assessments can be misleading.

Without reliable forecasting method, possibilities of future cost reductions were never anticipated and yet after the WEP was abandoned cost reductions continued to be observed. Learning curves can play a crucial role not just in assessment of historical trends, but in the extrapolation of costs into the future. However, extrapolation should be done with caution as it assumes constant innovation dynamics.

Learning curves are a useful tool for policy formulation for support of emerging renewable energy technologies that are not yet competitive. The effectiveness of learning curves might be improved if we do not neglect earlier development of technologies as we map out the future.

References

Alberth, S. (2007). Forecasting technology costs via the Learning Curve – Myth or Magic? Cambridge Working Papers in Economics Cambridge, Cambridge University.

Connor, P. M. (2003). "UK renewable energy policy: a review." Renewable and Sustainable Energy Reviews **7**(1): 65-82.

Davies, P. G. (1985). Wave energy: the Department of Energy's R&D programme 1974-1983- R-26. Harwell, Energy Technology Support Unit.
Dawson, J. K. (1979). Wave Energy Paper No 42. H. o. ETSU. Harwell, Department of Energy.
DEn (1980). A register of Energy Research, Development and Demonstration in the United Kingdom. DEn.
Elliot, D. (1987). Ruling out the waves. Milton Keynes, Network for Alternative Technology and Technology Assessment: 17.
ETSU, G. B. (1982). Strategic review of the renewable energy technologies an economic assessment. Harwell, Energy Technology Support Unit.
Garud, R. and P. Karnoe (2003). "Bricolage versus breakthrough: distributed and embedded agency in technology entrepreneurship." Research Policy **32**(2): 277-300.
Glendenning, I. (1977). Wave Power. Potential for Power- A Symposium on the Prospects for Power from Currently Unconventional Energy Sources, University of Southampton, The Institute of Fuel.
Gross, R., P. Heptonstall, et al. (2007). Investment in electricity generation- the roles, incentives and risks, UK Energy Research Centre-Technology and Policy Assessment.
Grove-Palmer, C. O. J. (1982). Wave Energy in the United Kingdom, A Review of the Programme June 1975-March 1982. The Second International Symposium on Wave Energy Utilization, Trondheim Norway.
Junginger, M., E. de Visser, et al. (2006). "Technological learning in bioenergy systems." Energy Policy **34**(18): 4024-4041.
Leishman, J. M. and G. Scobie (1976). The Development of Wave Power- A Techno-Economic Study. Department of Industry, NEL. Glasgow, East Kilbride, National Engineering Laboratory-Economic Assessment Unit.
Neij, L. (1997). "Use of experience curves to analyse the prospects for diffusion and adoption of renewable energy technology." Energy Policy **25**(13): 1099-1107.
Nemet, G. F. (2006). "Beyond the learning curve: factors influencing cost reductions in photovoltaics." Energy Policy **34**(17): 3218-3232.
Papineau, M. (2006). "An economic perspective on experience curves and dynamic economies in renewable energy technologies." Energy Policy **34**(4): 422-432.
Ross, D. (1979). Energy from the waves : the first-ever book on a revolution in technology. Oxford, Pergamon.
Ross, D. (2002). "Scuppering the waves: how they tried to repel clean energy from the waves " Science and Public Policy **29**(1): 25-35.
Thorpe, T. W. (1991). Wave energy review : interim report. [Chilton], Energy Technology Support Unit, Harwell Laboratory (Oxfordshire England).
Thorpe, T. W. (1992). A review of wave energy. Vol. 1, Main report. [Chilton], Energy Technology Support Unit, Harwell Laboratory (Oxfordshire England).
Thorpe, T. W. (1992). A review of wave energy. vol. 2, Appendices. [Chilton], Energy Technology Support Unit, Harwell Laboratory (Oxfordshire England).
Thorpe, T. W. (1999). A Brief Review of Wave Energy. ETSU;R120. Chilton, Energy Technology Support Unit Harwell Laboratory (Oxfordshire England).
Thorpe, T. W. and J. E. Marrow (1989). Wave Energy Review , Progress report No 1. ETSU Report- Chief Scientist Group. Chilton.

`