Australia's National Science Agency

Wave energy cost projections

A report for Wave Swell Energy Limited

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CSIRO Energy

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Executive summary

CSIRO was commissioned by Wave Swell Energy Ltd (WSE) to independently analyse the potential for capital cost and levelised cost of electricity (LCOE) reductions of its proprietary unidirectional oscillating water column (OWC) wave energy converter (WEC) technology. The analysis is based on the widely accepted concept of "learning-by-doing".

As to be expected, individual firm learning rate data was not available for WSE's WEC as it is a novel technology that has had limited deployment thus far. An estimated learning rate based on industry wide learning rates was used as the next best approach. It is not known how different an individual firm's learning rate might be compared to the industry wide learning rate, which is a source of some uncertainty in the methodology. In any case, a single firm cannot deliver all learning in a technology class such as wave energy and all technologies will benefit from collective learning. The wave energy sector's overall learning rate will, therefore, be the result of a concerted industry wide effort with support, for example, from government and the research sector.

Early stage or emerging technology classes have been found to have, on average, an industry wide learning rate (LR) of approximately 20%. However, using a bottom-up engineering approach, a more conservative LR of 18.23% was calculated for wave energy technology. Based on this LR, the capital cost was projected as a function of cumulative capacity out to 10,000 MW, and the LCOE was calculated alongside the capital cost.

At present, the WSE technology already has an LCOE that is competitive with diesel generation in remote locations. The modelling approach projected that the WSE technology can be cost competitive with offshore wind within 25 MW to 45 MW of installed capacity.

Applying an industry wide learning rate, it is projected that the WSE technology can achieve an LCOE of 0.05 $/kWh, which is equal to the current lowest cost generation of onshore wind and solar (Graham et al., 2020) if it can reach a deployment of 2,500 MW of installed capacity. This is approximately 0.35% of the installed capacity that onshore wind and solar PV have required to reach this same LCOE. As a comparison, the total global installed capacity for electricity generation was 7,484,000 MW at the end of 2019 (IEA, 2020), with wind and solar energy having reached 733,000 MW and 714,000 MW of this capacity respectively by the end of 2020 (International Renewable Energy Agency, 2021).

Using the CSIRO's global and local learning model (GALLM-E), which compares 27 electricity generation technologies under a scenario where the world heads towards net zero emissions by 2050, it is projected that wave energy, including the WSE technology, can achieve a 1.3% share of the global electricity market in 2050 if it can sustain an 18.23% learning rate. This equates to 170,000 MW of installed capacity and is greater than the total projected contribution of biomass and geothermal generation combined. Even if the learning rate halves over time, as has been the case for wind and gas turbines, for example, it can still achieve the same market share by 2050, however, early and large scale uptake would then be delayed by approximately 10 years.

The analysis in this report is based solely on reductions in capital cost. It does not take into account potential improvements in the conversion efficiency of the technology and, thus, any increases in the capacity factor. Technology improvements and increases in capacity factor are inevitable and have been observed to lead to greater proportional reductions in LCOE than for capital cost, implying the potential for an even lower LCOE for the WSE technology than projected in this report.

1 Introduction

CSIRO was commissioned by WSE to undertake cost projections of its proprietary wave energy converter (WEC) technology. WSE provided technology cost and performance data based on the company's experience with the UniWave200 King Island project, and the remainder of the data used is either publicly available through the GenCost project (Graham et al., 2021) or from other literature sources.

The report begins by reviewing the literature on technological development, with a focus on the early development stages, given wave energy and WSE's WEC is an emerging technology. The use of learning curves and learning rates (LRs) for projecting the future cost of a technology, along with methodologies for deriving an LR for WSE's technology as a wave energy device, are explained. Section 3 describes the methodologies and assumptions used in this study to determine the WSE LR, as well as those used to undertake future cost projections and the modelling to explore the future global electricity market potential for wave energy.

The calculated capital costs and levelised cost of electricity (LCOE) are presented in Section 4, expressed in Australian dollars (AUD). A sensitivity analysis of the LCOE to the underlying assumptions is also performed, along with an analysis of what LR and cumulative capacity are required for the LCOE of WSE's technology to be equivalent to that of established electricity generation technologies (using 2020 and 2030 cost estimates). This is followed by an analysis of the global market potential of wave energy, and a final discussion on the commercial implications to conclude the report.

2 Technology Development

Technologies progress through various stages in their development cycle, from the first invention through to senescence. Emerging energy technologies are in the early stages of development, sometimes known as the “formative phase”, and are typically characterised by demonstration projects and then deployment in niche markets. The focus of Section 2 is on the stage of development appropriate for wave energy and WSE’s WEC, as it is an emerging technology.

2.1 Characteristics of the early development stages

The formative phase represents the first steps of commercialisation (Grübler et al., 1999). “Technology push” occurs in these early stages, where research and development (R&D) investments are used to support emerging technologies to improve their performance and reduce their cost, allowing these technologies to begin deployment, particularly in niche markets where performance is often more important than cost. At the same time, niche markets provide “market pull,” i.e. ongoing demand for a new technology once technology push has reduced the gap between the incumbent technology and the emerging technology. “Technology push” and “market pull” mechanisms are used to drive deployment (Santhakumar et al., 2021; Wilson, 2012; Wilson and Grübler, 2011; Neij et al., 1997).

Emerging technologies in the early stages of commercialisation have not achieved consensus in terms of size of unit capacity and will continue ‘up-scaling’. Up-scaling refers to a general increase in output capacity of a given generation unit. There are examples of up-scaling across the broad spectrum of energy technologies, from fossil fuel power stations to renewables. Up-scaling can lead to significant cost reductions, which is one factor that results in high LRs for technologies at this stage of development (Wilson, 2012; Wilson and Grübler, 2011).

A good example of the impact of up-scaling on an emerging technology is wind energy. In Denmark, wind energy began its development by building lots of small unit sizes over several years and underwent significant learning before upscaling. Other countries focussed on rapid up-scaling to achieve cost reductions, but this resulted in a lack of learning at smaller (and thus cheaper) unit sizes and consequently failed (Wilson, 2012; Wilson and Grübler, 2011).

The length of the up-scaling phase depends on the characteristics of the technology in question. The historical data shows that it starts later and takes longer for technologies that have multiple applications and require different unit sizes. Examples of this are gas turbines and photovoltaics. Technologies with clear economies of scale in unit sizes, such as steam turbines, start up-scaling earlier and have a more rapid upscaling phase. LRs can slow down at the end of the up-scaling phase (Wilson, 2012; Wilson and Grübler, 2011; Grübler et al., 1999).

2.2 Learning-by-doing

The observed principle of 'learning-by-doing' states that the capital cost of a technology reduces as cumulative production of that technology increases. Furthermore, the costs tend to reduce by an approximately constant factor for each doubling of cumulative production (Wright, 1936; Arrow, 1962; Grübler et al., 1999). This is illustrated in Figure 1, which is a log-log plot of historical energy technology costs against cumulative capacity and shows how the costs have reduced as technological uptake has increased.

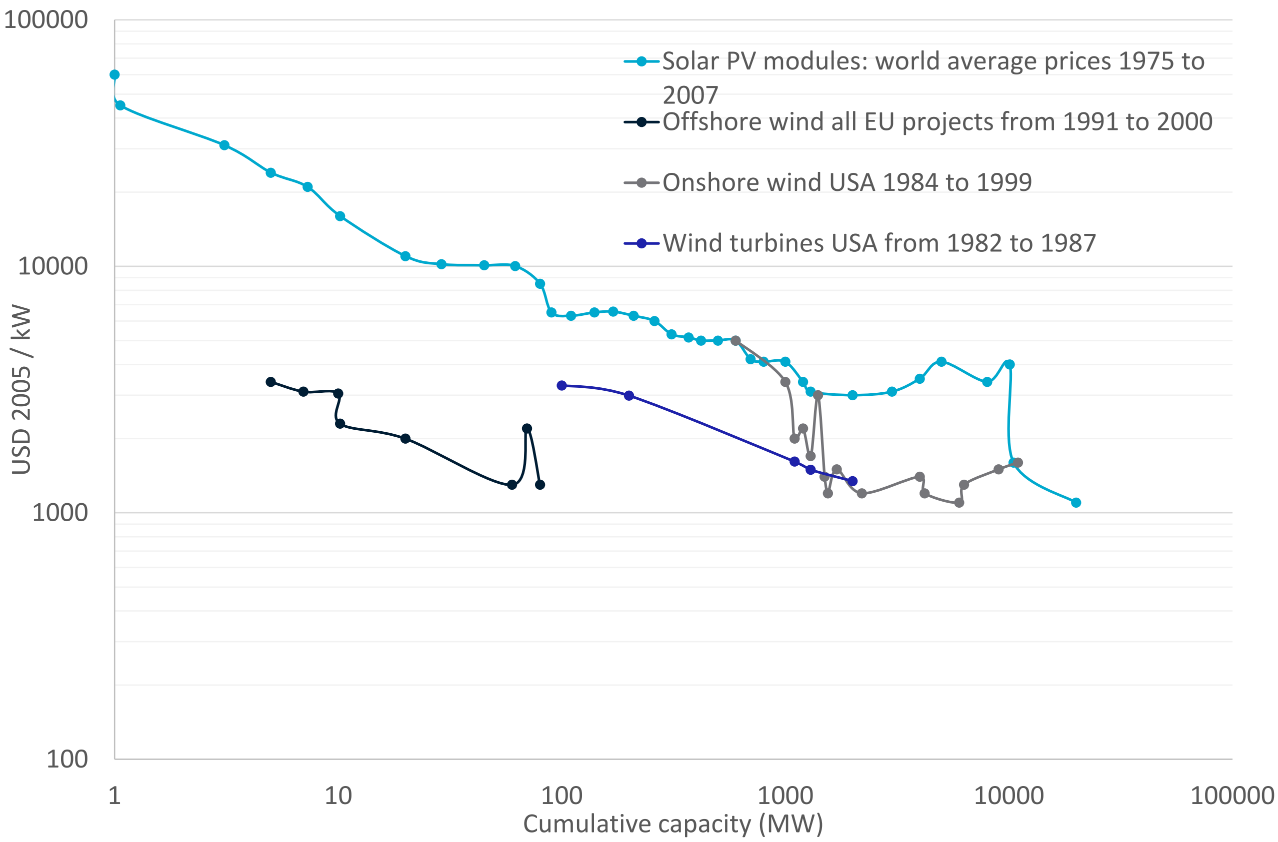

Figure 1 Historical technology costs versus deployment illustrating learning-by-doing. Source of data GEA (2012). PV=photovoltaics, EU=European Union, LR=learning rate, USA=United States of America, USD=United States Dollar. Wind turbines refer to just the component and onshore wind refers to onshore wind farms.

Learning-by-doing has been frequently applied to many technologies as it allows for the ability to create cost projections based on projections of the future uptake of a technology. Projections can be created from a transparent mathematical equation as follows:

$$IC_i = IC_0 \times \left(\frac{CC_i}{CC_0}\right)^{-b}$$

where IC_i is the investment cost of a technology at CC_i cumulative capacity at a given future point in time *i*, IC_0 is the investment cost at a given starting period and cumulative capacity CC_0, 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.

LRs and learning curves can be developed for an individual firm through to whole industries (Neij et al., 2003). They can be applied at the individual firm level to understand how production process costs can reduce costs through learning by doing as production increases, or to how a technology can reduce costs with uptake at a global level. Energy technology LRs that are available in the literature are generally based on a technology as a whole, such as wind turbines and the geographical scale can vary from a country to the whole world. There are very few published LRs for individual firms' technologies.

2.3 Learning rates

As discussed above, learning curves are based on historical cost and deployment data. While various wave energy devices have been deployed on a trial basis, they have all been located on the left hand side of the Grubb Curve (Figure 6) and there is insufficient historical cost and deployment data for wave energy and other new emerging technologies. In these circumstances, the LRs of analogous technologies at the same stage of development can be used. Observations of cost and deployment of energy technologies when in their early development stages, for example, photovoltaics, wind, and gas turbines, have revealed a general trend of a high LR of approximately 20% (Grübler et al., 1999). Figure 1 features technologies when they were in their early development stages, and the LRs, when calculated, are all close to 20%.

In fact, Grübler et al. (1999) observed that LRs in the range of 20% – 40 % are to be expected during the niche commercialisation phase, prior to the technology reaching a 5% market share (or approximately 1,350 TWh annually, based on 2019 global electricity production (IEA, 2020)). An LR of 20% is considered to be a good rule of thumb to use for emerging technologies (Jamasb and Köhler, 2008). Emerging technologies are situated in the first 'Early' learning stage in Figure 2.

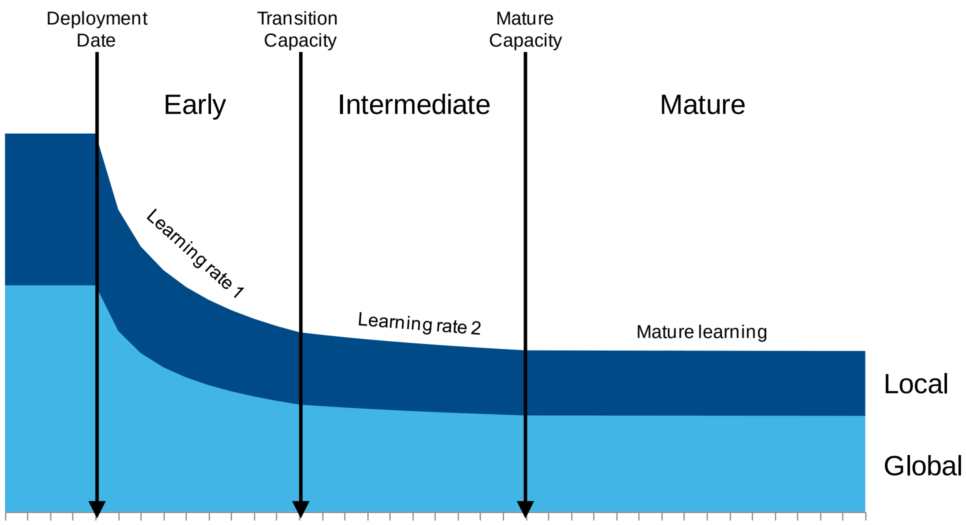

Figure 2 Schematic of changes in the LR as a technology progresses through its development stages after commercialisation

The high rate of learning observed for these early-stage technologies does not continue indefinitely. Several rates of learning can be observed for the same technology over its lifespan, and the rate depends on the stage of development of the technology. Typically, the LR reduces by approximately half as the technology matures (Grübler et al., 1999). The second LR is activated when the technology reaches the diffusion or intermediate stage, referred to as “Transition Capacity” in Figure 2. This occurs when the technology has reached approximately 5% market share (Grübler et al., 1999).

Once a technology reaches the mature stage, which corresponds to its lower LR limit, there is limited learning; however, there may be opportunities to reduce costs further by improvements related to materials etc.

Only the technology components, not labour components, have a second reduced rate of learning. Experience, particularly from the oil and gas industry, has shown that labour rates of learning tend to remain high even once the technology has become pervasive (Brett and Millheim, 1986; Schrattenholzer and McDonald, 2001).

2.3.1 Distribution of learning rates

It is instructive to examine the LR that different technologies have experienced during their evolution. One way to do this is by assembling the results of different studies that have been conducted into technology LRs. Schrattenholzer and McDonald (2001), Kahouli-Brahmi (2008) and the IEA (2008) compiled extensive lists of energy technology LRs. A histogram of the LRs is shown in Figure 3, with the LRs aggregated into bins of 4% increments.

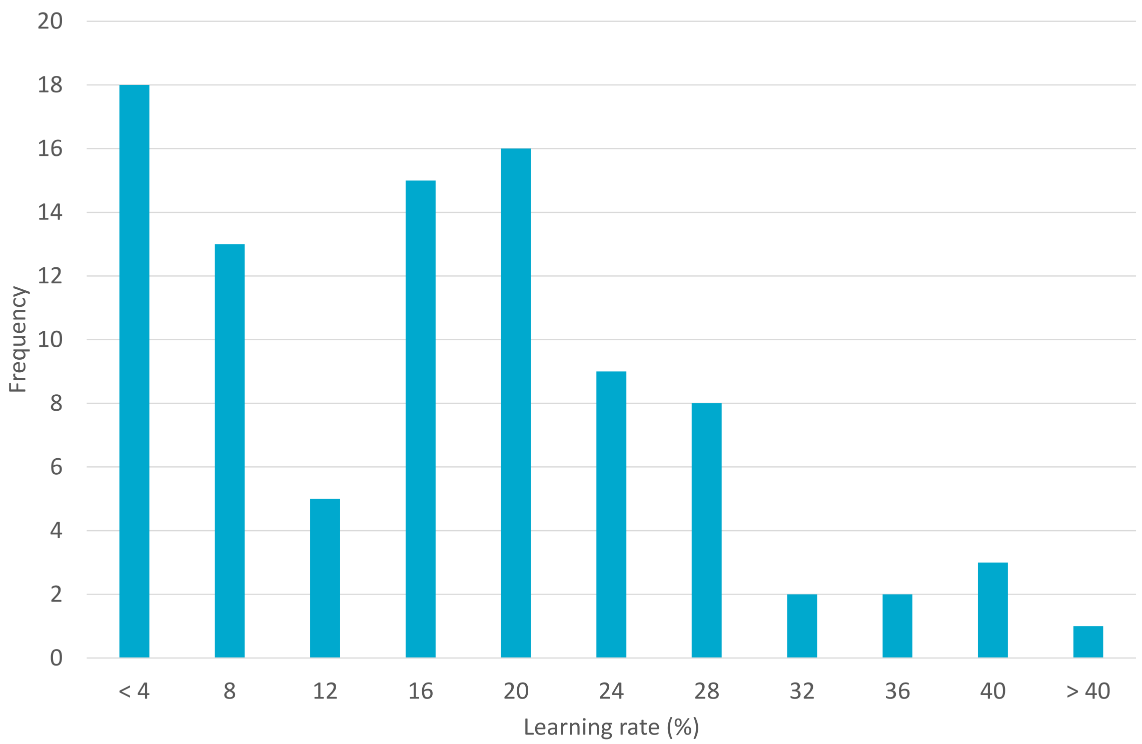

Figure 3 Histogram of 91 energy technology LRs

There are two modal values in the distribution, at 4% or less, and at 20%. The higher LRs tend to be associated with technologies in their early phases of development and are not just related to renewable technologies but also to fossil fuels. For example, an LR of 22% was calculated for gas turbines installed between 1958 and 1963. Solar PV modules exhibited a global LR of 20.2% between 1968 and 1998.

Mature technologies tend to have LRs of 4% and less. This includes combined cycle gas turbines from 1990 to 1998, and hydropower from 1975 to 1993.

The LRs of what can be considered to be early emerging technologies were extracted from the dataset, and a histogram showing the distribution of these emerging LRs is presented in Figure 4. In order to be classified as an emerging technology, the LRs needed to be calculated based on cost and cumulative capacity data from the early stages of deployment only. For wind turbines as a technology component and onshore wind farms, this meant that LRs beginning in the 1980s and ending in the 1990s were chosen. All solar PV LRs were chosen, and judgement based on CSIRO experience was used with the remaining technologies as to whether the dates were appropriate for an early-stage technology. If no dates were provided, the LR was not included.

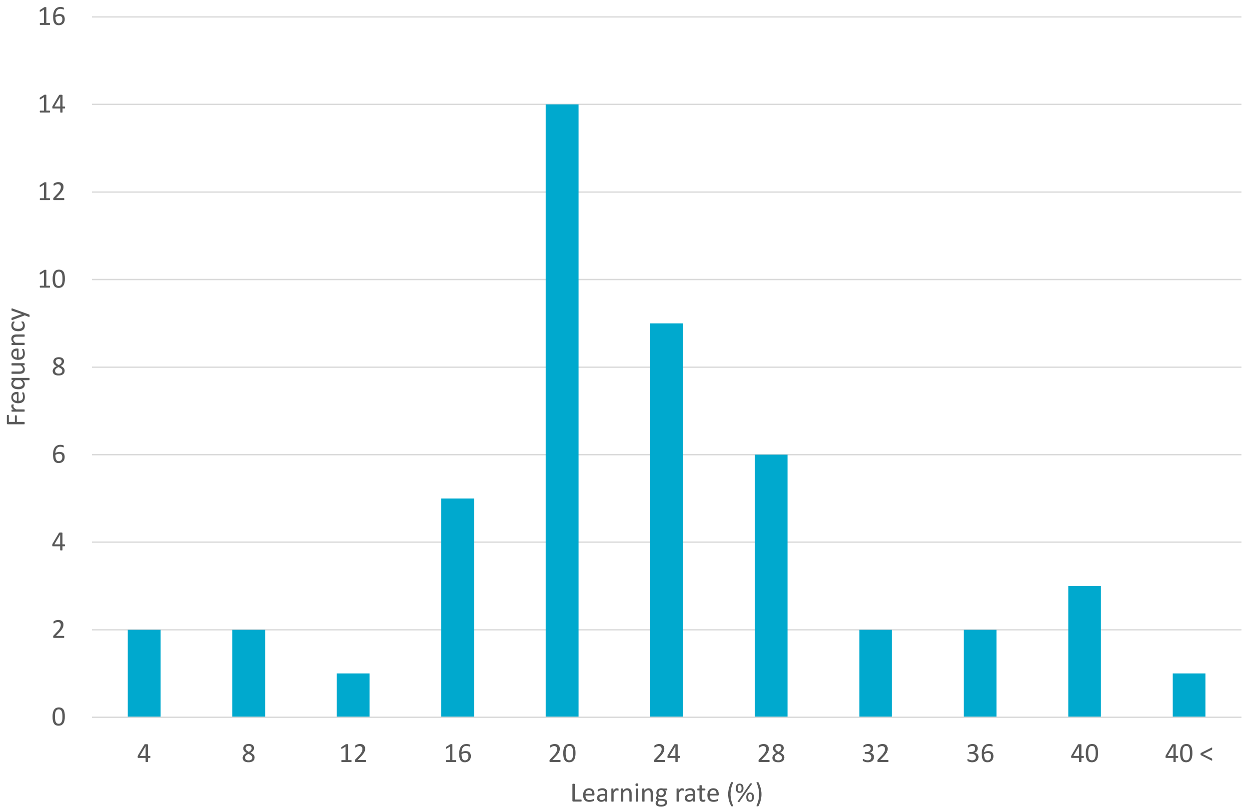

Figure 4 Histogram of 47 emerging technology LRs

Using the data presented in the histogram above, it is possible to elicit various statistical information: mean = 21.5%, median = 20%, mode = 20%. The minimum is 4%, and the maximum is 41.5%.

Additionally, based on the distribution of this LR data, 70% of all emerging LRs observed in these studies are above 18.23% (this statistic is of later relevance in Section 3.1).

2.4 Limitations of using learning curves

There are limitations in adopting the learning curve approach. The first is that it is not a law; it is based on observations. It does not include sudden technological changes, market shifts and other factors which can impact the rate of cost reduction. Cost reductions are the accumulation of several factors, not just learning by doing, which, in most cases, cannot be separated.

These other factors are well understood and include economies of scale, both in manufacturing and installation and knowledge spillovers (where learning is shared between technologies and regions). Cost overruns in the early stages of a technology's deployment can skew learning curves upwards, but they need to be included, as they are part of the process of technology development.

There are also other forms of learning which tend to be wrapped up into learning by doing, as again, they impact cost reductions. Learning-by-researching is important for emerging technologies, as it occurs during the R&D process and before commercialisation. Learning by researching is supported by R&D investments and leads to improvements in the technology and cost reductions. This also leads to a greater likelihood of technology deployment, and thus supports other aspects of learning by doing (Kahouli-Brahmi, 2008).

In addition, LRs vary depending on the time period over which they are measured, which is related to the observations made by Grübler et al., (1999). It is important that an appropriate data set is used when comparing technologies at similar stages of their commercialisation.

A good example is the offshore wind industry, where the first decade of commercialisation exhibited an LR of just over 18%, while the period 2010-19 resulted in a lower LR of about half that, partially due to extraneous market factors. This case is elaborated upon in Section 2.5.

It has been shown that at least 10-12 years or 2-3 magnitudes of cumulative output data is required to produce a stable estimate Santhakumar et al., (2021).

2.5 An emerging technology case study – offshore wind

The early stages of offshore wind's development from 1991 and into the early 2000's can provide some insight into LRs for wave energy as an emerging technology being deployed in the ocean. Junginger et al., (2004) estimated a 38% LR for the installation cost of interconnection cables and 29% for high voltage direct current (HVDC) converter stations. A 23% LR was estimated for the installation cost and, at the time, the actual construction of wind turbines had a LR of 15% to 19%. The breakdown of an offshore wind project's cost into contributions from each component as an emerging technology is shown in Table 1.

Table 1 Breakdown of offshore wind cost components during its early development phase (Junginger et al., 2004)

Component	Share of the total cost (%)
Turbine	30 - 50
Foundation	15 – 25
Internal grid and grid connection to shore	15 – 30
Installation	0 – 30
Other costs	8

Junginger et al., (2004) did not estimate a total offshore wind farm LR; however, applying a weighted average of the individual component LRs against their relative contribution to the total capital cost, suggests an overall LR of close to 20%.

As an emerging technology from 1991 to the early 2000's, offshore wind would be situated in the "Early" stage as shown in Figure 2. However, now that offshore wind is an 'intermediate' technology, its capital cost based LR has slowed. But, before this occurred, there was a period in the mid 2000's where there was a lack of wind turbine supply and increased demand which impacted the cost of both onshore and offshore wind. This increased the price of offshore wind, as can be seen in Figure 5. By including this price increase (due to market factors) in the calculation of the long-term LR of offshore wind, the apparent LR is reduced considerably.

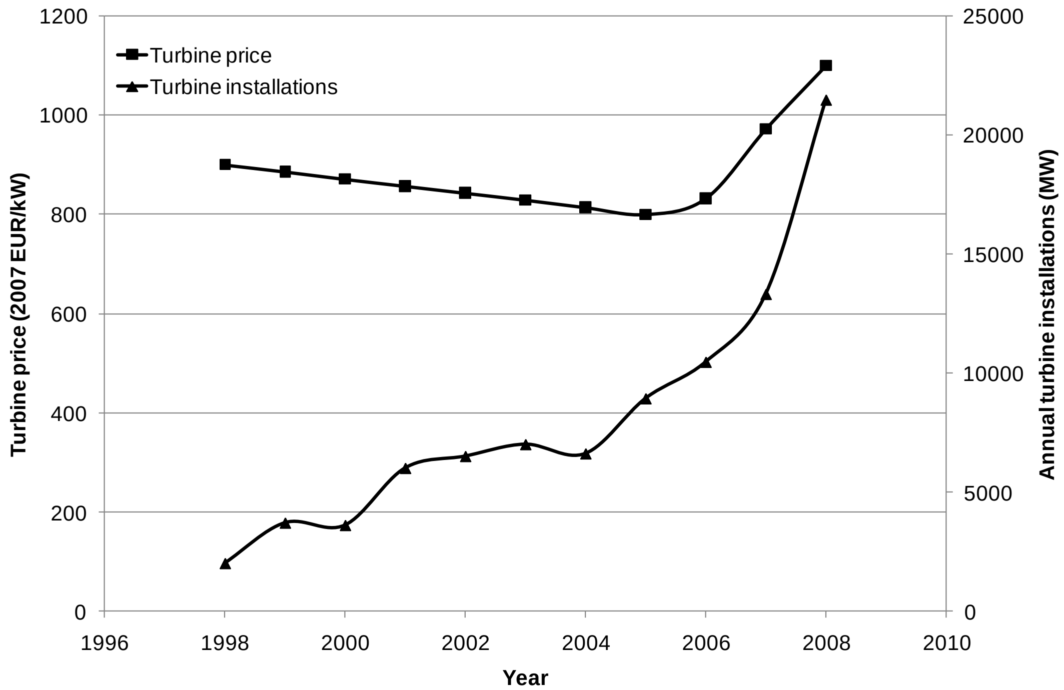

Figure 5 Wind turbine price and annual installations in IEA countries (Hayward and Graham, 2011)

Offshore wind underwent a shift in focus around the year 2010 from reducing the capital cost to reducing LCOE. Subsequent reductions in LCOE have been achieved by many factors, including moving to deeper waters, increasing farm scale, and increasing turbine blade length and hub height. These changes have led to increases in the capacity factor and thus reductions in the LCOE (IRENA, 2016), even while reductions in unit capital cost have been slowing. Innovations have also been occurring to reduce operations and maintenance (O&M) costs, improve control and, as the developers gain experience, they will be able to access lower cost finance. This will reduce the weighted average cost of capital (WACC)/discount rate so it does not include a risk premium and, thus, further reduce the LCOE (IRENA, 2016).

The combination of increasing turbine prices, moving to deeper waters, and the shift in focus from reducing the capital cost to reducing LCOE, has led to low long-term capital cost LRs for offshore wind of less than 5% (Santhakumar et al., 2021). IRENA calculated a capital cost learning rate for offshore wind using the last 10 years of data which is 9%, almost double the long term rate (IRENA, 2021a).

2.6 Estimating a learning rate

Wave energy, and WSE's WEC , are clearly at the early commercialisation stage and are therefore defined as emerging technologies. There are three approaches that can be taken to estimate a LR for wave energy at this stage of its development:

(1) Apply a *rule-of-thumb*. The literature that has focussed on the early formative phases of a technology's development have all shown a high LR of ~20% across a range of energy technologies. This is considered to be a rule of thumb LR. An LR of 20% has been achieved or exceeded by solar PV and both onshore and offshore wind during their formative phases and beyond.

(2) Use an LR from a similar technology at the same stage of development. Offshore wind and wave energy should have many similarities, given they share the same difficult ocean environment. LRs have been calculated for each of the components of offshore wind when it was in its early development phase (Junginger et al., 2004). These indicate a resulting composite LR for the early stage of offshore wind of 18.3% (see Figure 8).

(3) Break wave energy down into its components and estimate a LR based on a bottom-up assessment of the costs and individual LRs of each component. Santhakumar et al., (2021) suggest taking this approach for wave energy, an approach that was used by Junginger et al., (2004) to estimate the early offshore wind LRs (as per point (2) above).

The IEA (2020) quotes an ocean energy LR of 14%. It is not known what is behind this value, given there is no cost reduction data for ocean energy from which to estimate a learning rate. It may be based on a longer-term trend LR for offshore wind, which the IEA assumes is 15%. However, this longer-term trend includes the period when the supply of wind turbines could not match demand, which resulted in price increases unrelated to learning, which would artificially deflate the apparent offshore wind LR if those data points were included.

2.7 The technology learning environment

In trying to understand what may happen in the future with wave energy and WSE's technology it is useful to look at the period during which another technology was emerging and has achieved success – wind turbines in Denmark.

Wind has been deployed for centuries however it wasn’t until the 1970s that the modern wind industry began to appear, which was driven by the global oil crisis. Denmark was particularly impacted by the oil crisis as oil provided 94% of its primary energy needs. Denmark decided to pursue wind energy as it has a strong wind resource and no substantial hydro or coal resources. The government directed the Danish Nuclear Laboratory (RISØ) and the Technical University of Denmark to research wind energy. At the same time, there were many amateur wind turbine developers taking advantage of the windy conditions and building their own turbines. Vestas was formed in the 1970s off the back of one of the amateur designs, which later became known as the “Danish concept” and consists of the three-blade turbine used today with fibreglass blades. Other companies started emerging as government support increased via loans and subsidies for renewable energy investment. By 1980 there were 10 turbine manufacturers however these eventually merged into either Vestas or later Siemens Gamesa. Vestas was the first company to mass produce a wind turbine and is still a world leader (Owens, 2019). Vestas did not become a world leader on its own. Vestas was supported by a whole learning environment focussed on wind energy in Denmark, with support from the government, the research community, other wind turbine developers and the public.

There have been designs for wave energy devices for many years; by 2012 there were at least 200 (CSIRO, 2012). However, only a handful of devices have been tested and trialled at sea. Some early devices had design and technical issues with hydraulic fluid, for example, or there were issues with the business itself and financing. The wave energy industry as a whole has learnt from these earlier trials and now there are fewer companies and designs and the newer designs, such as WSE’s, are based on a simple point absorber or an OWC with very few moving parts. While there is less direct government support in Australia for wave energy as there was in Denmark for wind, there is a recognised global need to move the world towards net zero emissions by 2050, which will require a suite of renewable energy technologies and in particular, technologies that can provide some dispatchable power, such as wave energy. Given this imperative, further support for wave energy should be realised.

The wave energy industry as a whole is emerging and, by continuing to cooperate through sharing knowledge and with support from the research community, this will lead to cost reductions which contribute to learning-by-doing.

3 Methodology

3.1 WSE Learning rate

With only a single unit installed, WSE does not have an individual firm learning rate and there are no other examples available of individual firm learning rates in the wave energy sector. The only alternative, therefore, is to use an industry wide learning rate. The use of industry wide learning rates applied to an individual firm creates some uncertainty in the applicability of the data but is unavoidable due to data limitations.

Applying a bottom-up approach, that is a combination of Options 2 and 3 from Section 2.6, where the relevant component LRs from the offshore wind industry, highlighted in Junginger et al., (2004), are used and weighted against the relative cost of these components for the WSE technology, indicates an overall LR of 18.23%. The details of this calculation are shown in Table 2.

Table 2 Bottom-up calculation of WSE LR. Source WSE.

Component	CAPEX ($/kW)	LR (%)	Weighted LR (%)
Power take-off	2,983	19	4.07
Foundation	1,365	10	1.07
Structure	5,400	18.3	5.23
Grid connection	846	20	1.43
Installation	2,348	23	4.93
Other	989	14	1.50
Total	13,931	-	18.23

Given that all three of the methods from Section 2.6 suggest a consistent LR of 18-20% for the niche commercialisation phase of wave technology, it is considered appropriately conservative to apply the LR value derived from the bottom-up approach to the further analysis of this report, which includes using it as an industry-wide LR and for WSE as an individual firm.

As was shown in Section 2 of this report, 70% of all emerging energy technologies studied exhibited LRs higher than 18.23%. Therefore, this bottom-up LR of 18.23% was chosen for use in subsequent calculations.

3.2 Capital cost projections

In order to project capital cost reductions due to learning by doing, a projection of the future cumulative capacity of the technology needs to be determined. This can be undertaken using a model, as is described in Section 3.4, or a simple approach can also be used, which is to assume a continuous increase in cumulative capacity, up to 10,000 MW in this case. There is no need to include a time element to this type of projection as the capital cost is dependent on cumulative capacity, not time.

Capital costs of a technology do not necessarily begin to decline from the first installation. Typically, costs increase as more is understood about the technology and difficulties arise with real-world installations. Once a technology overcomes the pilot and demonstration phases, the costs may begin sustained declines. This process is illustrated by the Grubb curve as shown in Figure 6.

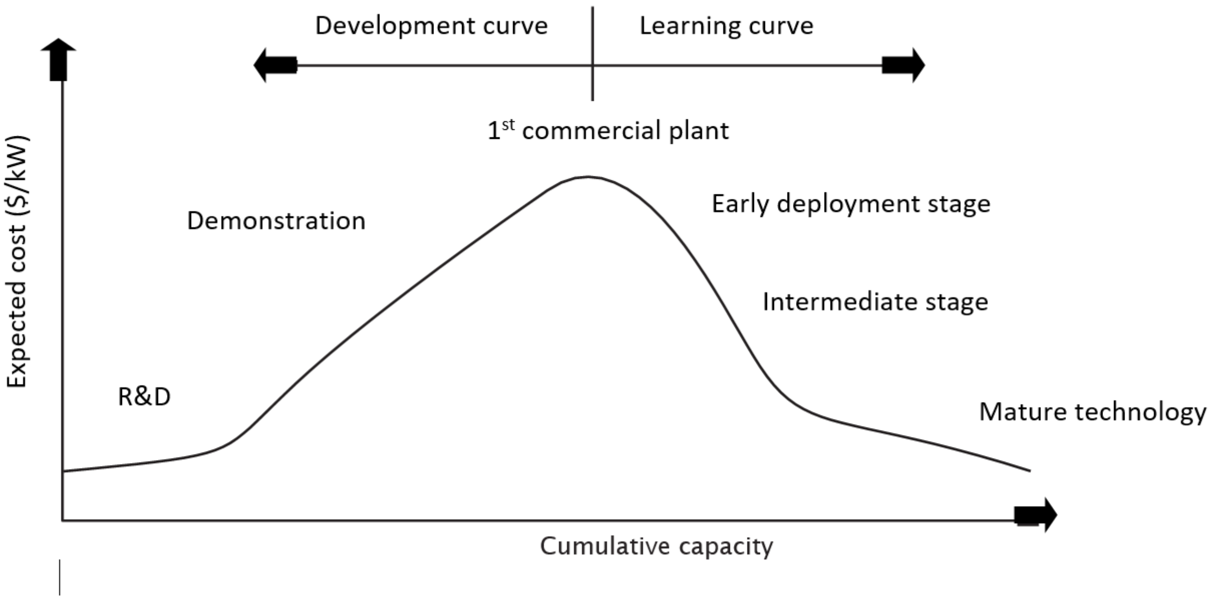

Figure 6 Stylised Grubb Curve (Smitham and Hayward, 2011)

WSE's WEC is at a technology readiness level (TRL) of 9[1] and a commercial readiness index (CRI) of 2[2], having demonstrated its technology via the construction, installation, and operation of its King Island installation in Tasmania. The King Island project has allowed WSE to understand its cost base in detail, along with requirements for installation, operation, and likely future maintenance, thereby overcoming its initial cost hurdles. WSE states that the technology is now about to enter its commercial phase, placing it at the peak of the Grubb Curve. It is expected that sustained cost reductions will occur in future deployments of this technology.

[1] TRL9 - Actual system proven through successful operations: Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

[2] CRI2 - Commercial trial: Small scale, first of a kind project funded by equity and government project support. Commercial proposition backed by evidence of verifiable data typically not in the public domain.

3.3 Levelised cost of electricity

The levelised cost of electricity (LCOE) is a metric commonly used to compare the cost of generating electricity between different technologies. It represents the cost only; it does not include revenue, taxes or depreciation.

The standard formula for the LCOE in \$/MWh is

$$LCOE = IDC \times \frac{r \times (1+r)^L}{(1+r)^L - 1} \times \frac{K}{8760 \times Capfac} + \frac{O\&M_{FIX}}{8760 \times Capfac} + O\&M_{VAR}$$

where r is the discount rate, L is the lifetime, K is the capital cost in \$/MW, Capfac is the plant capacity factor (as a ratio), $O\&M_{FIX}$ is the fixed operations and maintenance (O&M) cost in \$/MW/year, and $O\&M_{VAR}$ is the variable O&M cost in \$/MWh.

IDC is the interest during construction which is paid over the construction period. It is given by:

$$IDC = \sum_{i=1}^{P} \frac{1}{P} \times (1+r)^{(i-1)}$$

where P is the construction period in years. This formula assumes the same annual payments during the construction period.

The LCOE has been calculated for WSE's WEC at various levels of cumulative capacity.

To explore the sensitivity of the LCOE to each assumption, Tornado charts have been calculated. Each assumption has been varied by ±25% to examine their impact on the LCOE.

3.4 Global electricity sector potential

The use of a modelling framework with the learning curves at its core allows for the uptake of the technology to be determined at the same time as the cost reductions i.e. simultaneously.

CSIRO developed the Global and Local Learning Model – Electricity (GALLM-E), which features endogenous technology learning, using learning curves for intermediate and emerging technologies and 13 world regions with electricity demand. GALLM-E is solved as a mixed integer linear program where costs are minimised to reach a given level of electricity demand. Projected global and regional electricity demand has been sourced from the IEA (2020). For more information on GALLM-E see Graham et al. (2021) and Appendix A of this report.

Energy models include broad technology classes such as wave energy. They are unable to distinguish the contributions of individual technology providers as that would become computationally intractable and there is insufficient data to enable this. There is also the issue of technology lock-in, where such a model will tend to choose the least-cost technology to the exclusion of others. In reality, a technology may be used in a particular application for reasons besides cost, which cannot be included in a model of this type. The WSE technology fits into the broad class of wave energy technologies, which is how it has been modelled in GALLME. The assumptions presented in Table 3. All other assumptions remain the same as in the 2020-21 GenCost report (Graham et al., 2021).

Including wave energy in GALLM-E means that it is in global competition with 27 electricity generation technologies to install capacity and contribute to regional electricity generation with existing and new generation capacity. The least-cost electricity generation mix is chosen by the model, within constraints such as land and biomass availability, renewable resources, and climate policies.

A capital cost trajectory over time will be extracted from the results and used to calculate the LCOE.

3.5 Technology cost and performance assumptions

Two scenarios have been modelled using the global electricity sector model, Achievable and Conservative, with the key assumptions presented in Table 3. The Achievable scenario has a continuous 18.23% LR and the Conservative scenario begins with an 18.23% LR but it reduces to 9% as cumulative capacity increases to 20,000 MW, simulating the transition from an emerging to an intermediate technology.

The simple capital cost projection method has been applied to a single learning rate, which corresponds to the Achievable scenario. The sensitivity of the LCOE to changes in the Achievable scenario assumptions will be determined as stated in Section 3.3.

Supported capacity refers to government supported technology investments, which can start a technology's journey down the learning curve. GALLM-E has such support for all emerging technologies including carbon capture and storage, tidal energy and small modular nuclear reactors.

Table 3 Key assumptions

Assumption	Units	Achievable	Conservative	Sources
LR	%	18.23	18.23 and 9	WSE bottom-up calculation
O&M cost	% of capital cost	3.02	3.02	IEA (2020)
Initial capacity factor	%	35	35	WSE
Construction time	years	1	1	WSE
Lifetime	years	25	25	Graham et al. (2021)
Discount rate	%	5.99	5.99	Graham et al. (2021)
Supported capacity	MW	10	750	

The capital cost of the WEC is 14,000 $/kW. This was used as the current technology cost. The technology only has a single fixed percentage O&M cost. There is no variable O&M cost.

The capacity factor has been kept constant. However, it is expected to improve with deployment as more is understood about the resource and about how to improve the efficiency of converting wave energy into electrical energy. An increased capacity factor will lead to an even lower LCOE than that projected through capital cost LRs alone.

The LCOEs of the comparison technologies: solar PV, onshore wind, offshore wind and diesel generators were sourced from Graham et al., (2021). The diesel fuel price was assumed to be

1.328 $/L, which was the weekly national average wholesale price for the week beginning 15 August 2021[3]. Stationary energy diesel users can claim the diesel fuel rebate and this was not included in the calculation. However, this saving may be offset by transport costs to remote locations which is where diesel tends to be used for stationary energy. Because of this uncertainty, the calculation has been based on the price listed above.

[3] https://www.aip.com.au/sites/default/files/download-files/2021-08/Weekly%20Diesel%20Prices%20Report%20-%2015%20August%202021.pdf

4 Results

4.1 Current LCOE

As a new technology, WSE's LCOE is higher than more established forms such as coal, wind, and solar PV. However, all forms of energy production decrease over time as more capacity of that technology is installed, with the decrease in cost being most rapid in the early phase of the technology's commercialisation. The WSE technology is generally cost competitive with the diesel-based generation that is endemic in remote locations, particularly islands. These locations are logical niche markets for the WSE technology in the immediate term, as many are surrounded by an abundant wave energy resource. Figure 7 illustrates the LCOE of the current WSE 1 MW UniWave WEC with the LCOE of other forms of electricity generation.

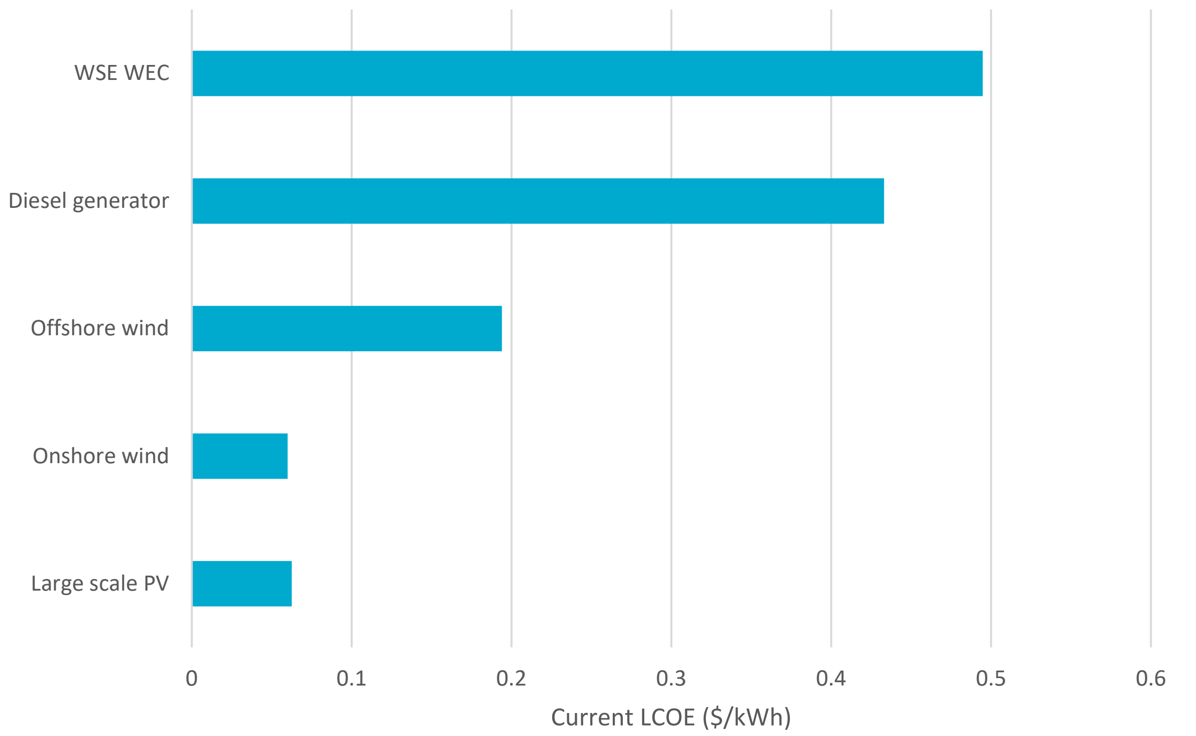

Figure 7 LCOE of WSE's WEC and other electricity generation technologies

Note, for the LCOE of WSE's WEC to break even with that of the diesel generator from Day 1, the price of diesel needs to be 1.58 $/L.

4.2 Projected capital cost and LCOE

Figure 8 shows the projected capital cost reductions of the WSE technology, using the fixed industry wide 18.23% LR defined in Section 3 that does not reduce as cumulative capacity increases, along with historical cost reductions of technologies when they were in the early learning phases. The currency units are USD 2005; therefore the WSE WEC costs were converted to USD from AUD and deflated to 2005 to be consistent with the other technology's costs.

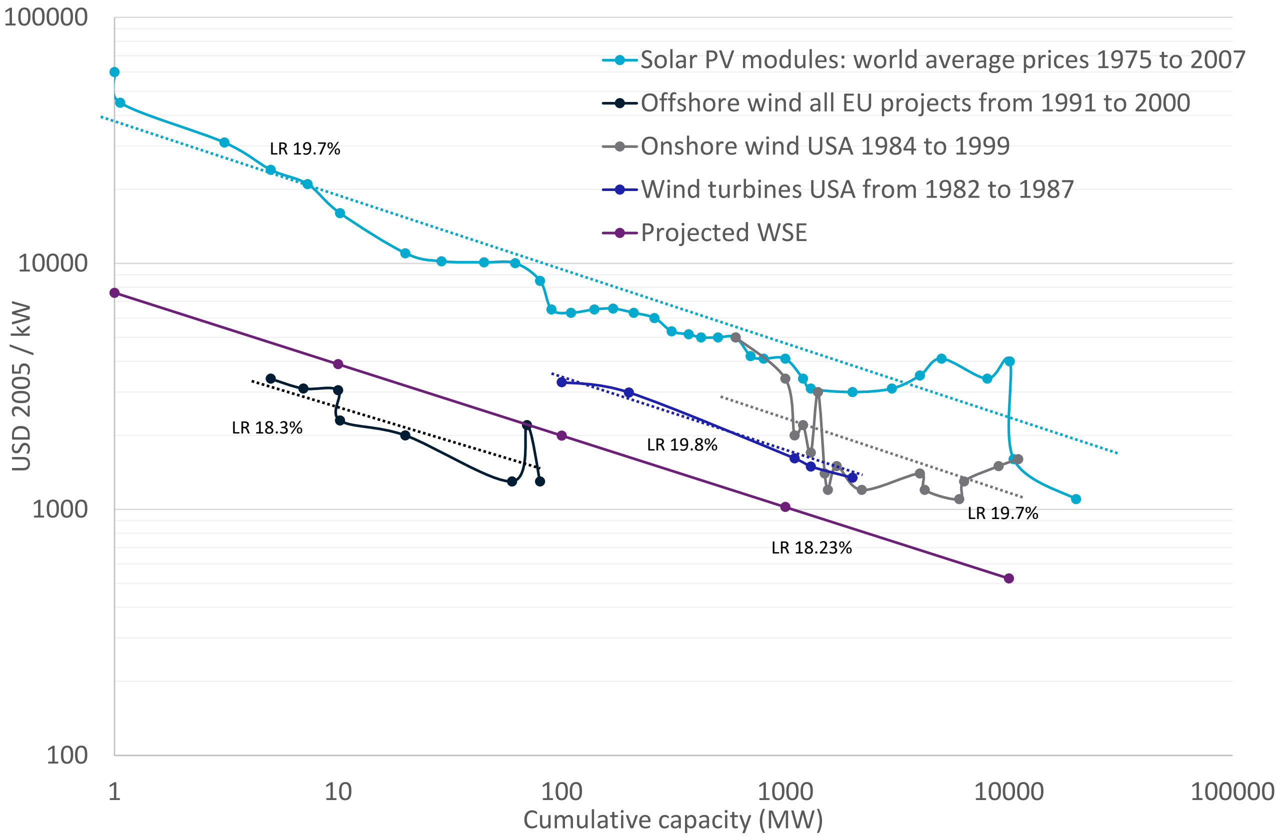

Figure 8 Projected capital cost with an increasing cumulative capacity

If WSE, as an individual firm, can achieve learning rates consistent with industry wide learning, the projected capital cost and LCOE of the WSE technology in AUD 2020 is shown in Figure 9. The present day LCOEs of large-scale PV, offshore and onshore wind, and diesel generators have been overlaid for comparison purposes. This figure illustrates at what cumulative capacity the LCOE of WSE should equal that of the current cost of various other technologies, noting that while this a comparison against the current cost of wind and solar PV, the LCOEs of these technologies will also continue to decrease with uptake. The breakeven cumulative capacities of WSE with the current LCOE of various technologies are shown in Table 4.

Table 4 Cumulative capacity at which the LCOE of WSE calculated using an 18.23% LR is equivalent to that of the current cost of other technologies

	Diesel generator	Offshore wind	Onshore wind	Large scale PV
Breakeven cumulative capacity (MW)	1.6	25.3	1422	1203

The industry wide LR of 18.23% leads to capital costs reducing to 3676 $/kW by the time 100 MW have been installed and 1022 $/kW when the cumulative capacity reaches 1000 MW. Since the O&M cost is a percentage of capital cost, it will also reduce at the same rate. The current O&M cost is 423 $/kW/annum, and this will reduce to 31 $/kW/annum when the cumulative capacity reaches 1000 MW. The associated LCOE at 1,000 MW of cumulative capacity is 0.07 $/kWh, dropping to 0.05 $/kWh by 2,500 MW.

To achieve and maintain the 18.23% LR and the associated cost reductions, the focus needs to be on actions that can increase the impact of learning-by-doing, i.e. achieve cost reductions while deploying the technology, scaling up manufacturing, and building economies of scale through deploying larger units, which will be dependent on site conditions and by deploying multiple devices into larger wave farms.

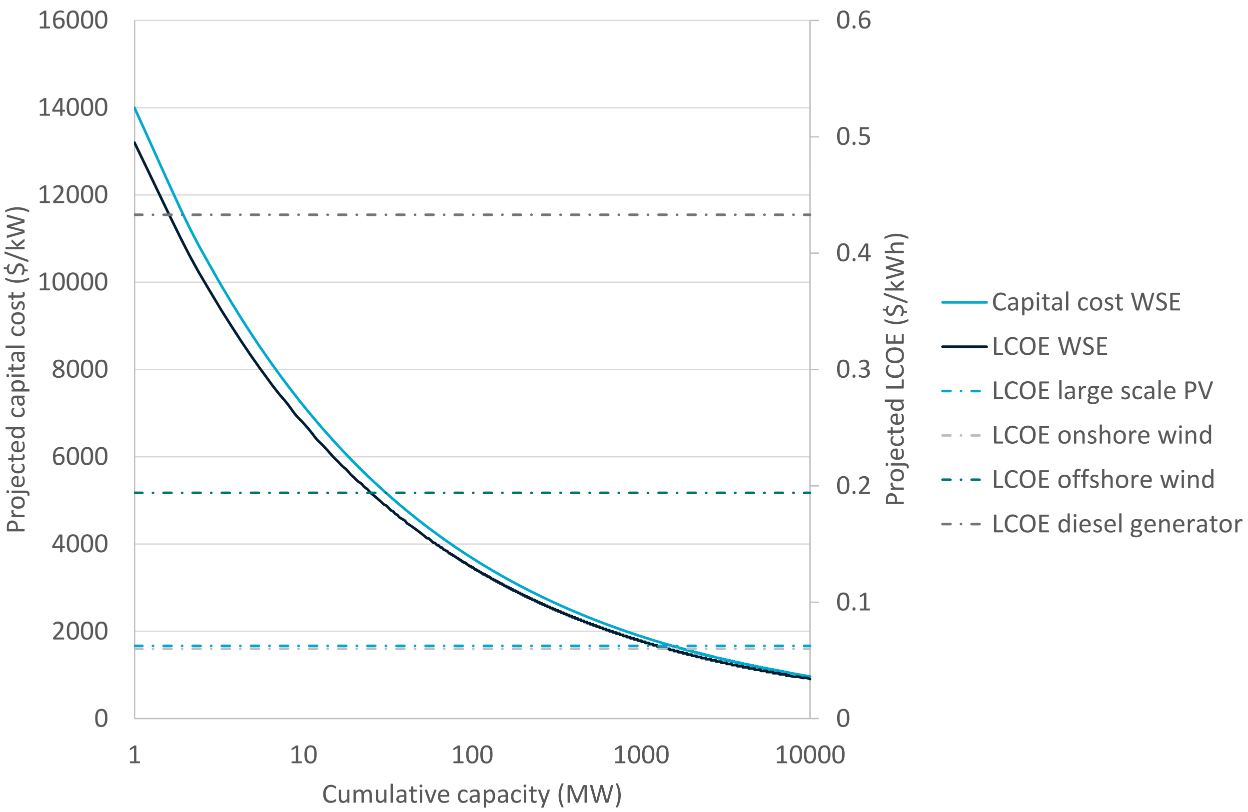

Figure 9 Projected capital cost and LCOE of WSE's WEC with increasing cumulative capacity along with the current LCOEs of various technologies

4.3 Cost parity analysis

Figure 10 and Figure 11 illustrate the amount of cumulative capacity of the WSE technology that would be required, at various LRs, in order to reach cost parity with various other technologies in

2020 and 2030 respectively. These other technologies have a range of LCOE based on the results from Graham et al., (2021).

It can be seen in both figures that the WSE technology is almost competitive with diesel generation in remote locations and is, therefore, quite insensitive to LR in that case. Other technologies, however, demonstrate variability with LR. In all cases, as is logical, a higher LR results in the WSE technology achieving cost parity at a lower cumulative capacity. As would be expected, Figure 11 shows that a higher cumulative capacity is required to match the expected lower LCOEs of these technologies in 2030. In 2030 and at a 20% LR for the WSE technology, a cumulative capacity of 32 to 35 MW and between 600 and 1,300 MW is required to compete with offshore wind and onshore wind respectively. At a 15% LR, 120 to 129 MW and 6,140 to 17,270 MW of cumulative capacity is required for WSE's LCOE to match that of offshore wind and onshore wind, respectively. As a basis for comparison, the current total global electricity generation capacity is 7,484,000 MW (IEA, 2020).

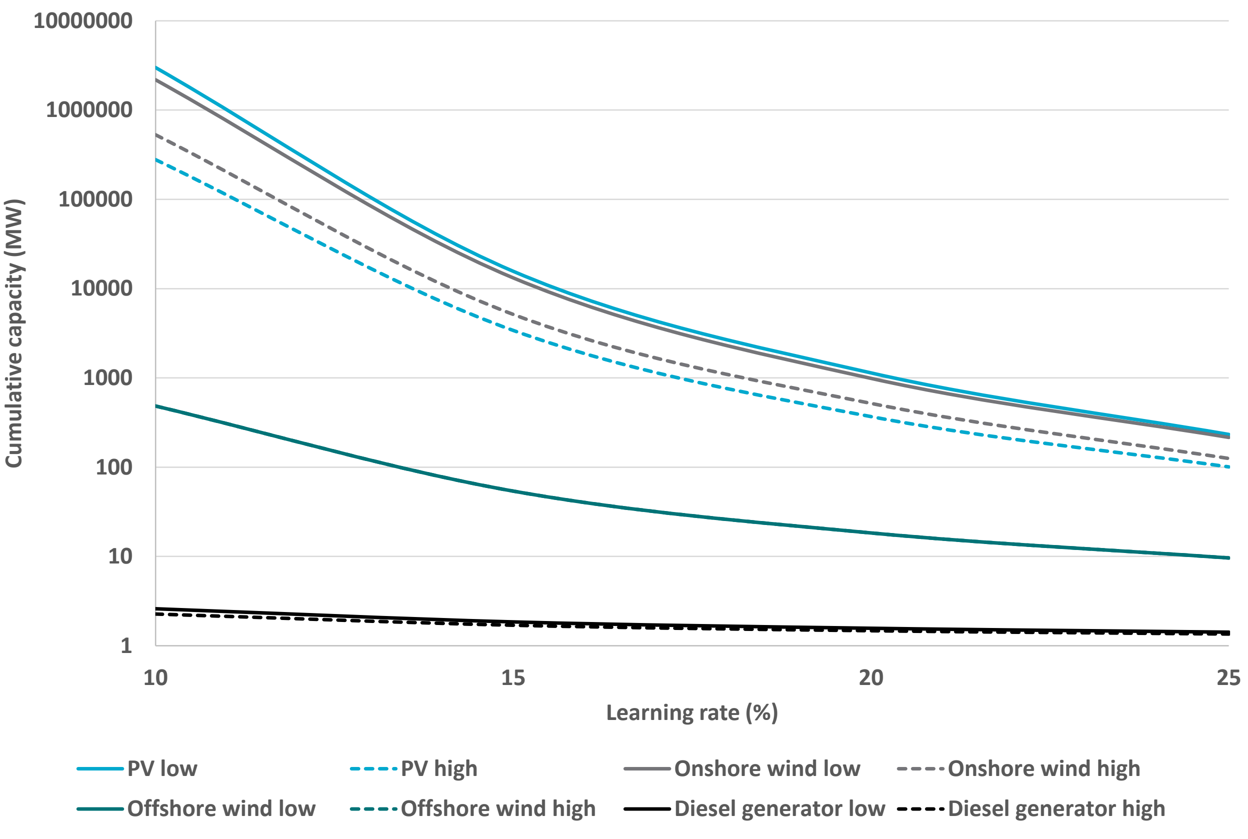

Figure 10 LR and cumulative capacity where the projected LCOE of WSE's WEC is equivalent to that of other technologies in 2020

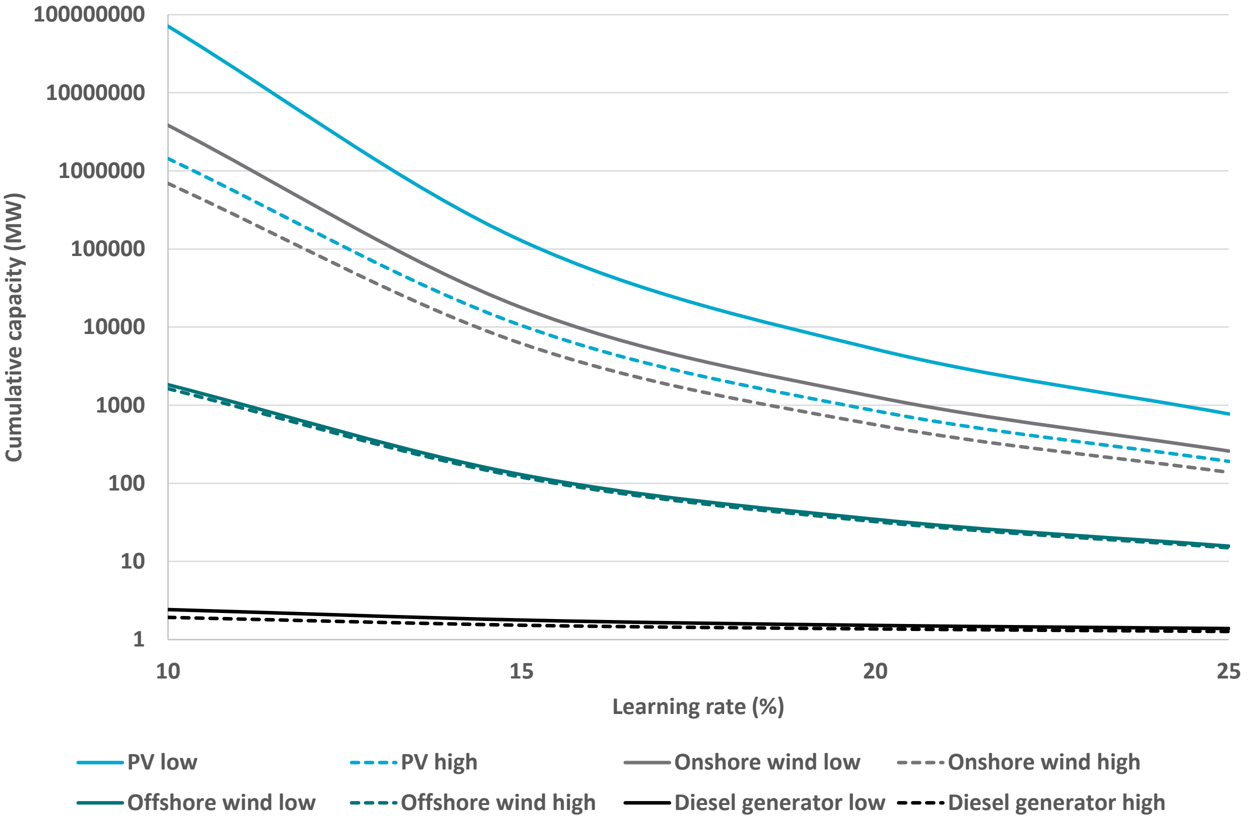

Figure 11 LR and cumulative capacity where the projected LCOE of WSE's WEC is equivalent to that of other technologies in 2030

Figure 12 and Figure 13 illustrate similar sensitivities, only now with LCOE plotted against cumulative capacity for discrete LRs across the LR range of the previous graphs, for the years 2020 and 2030 respectively. Horizontal coloured lines represent the breakeven points where the WSE technology matches the LCOE of other technologies (the very similar LCOEs for onshore wind and solar PV result in an overlay of their horizontal lines in the 2020 case).

Again, it can be seen that the WSE technology is competitive with diesel generation at a low cumulative capacity and at any LR. Other technologies, however, require more cumulative capacity for WSE to be competitive, with less capacity required when LRs are higher. For example, at 2020 LCOEs and at a LR of 15%, the WSE technology reaches parity with diesel at a cumulative capacity of 1.7 MW, with offshore wind at 54 MW, and with onshore wind and solar PV at ~7,000 MW. At a 20% LR these capacities drop to 18 MW and 700 MW for offshore wind and solar PV / onshore wind respectively. By 2030, the corresponding capacities are 125 MW and 10,000 MW at an LR of 15% for offshore and onshore wind respectively, and 34 MW and 800 MW at 20%. Interestingly, by 2030 solar PV is predicted to be at a lower cost than onshore wind as it has a higher ongoing LR.

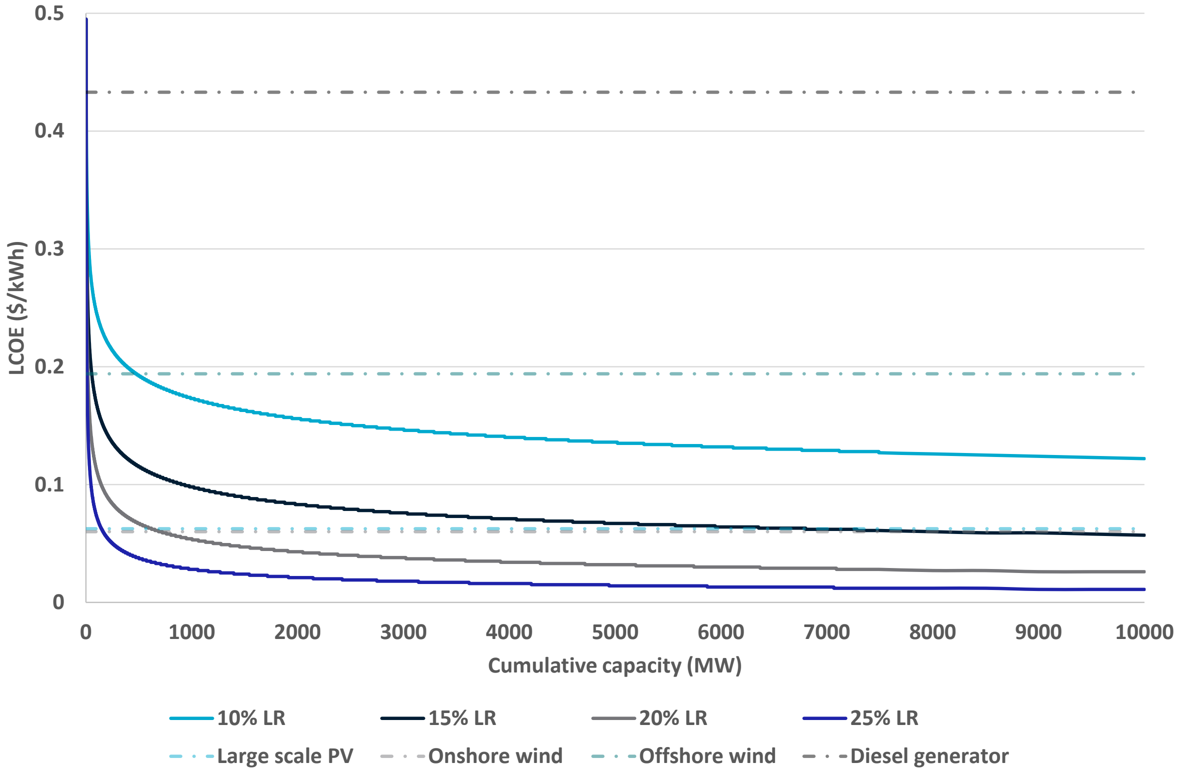

Figure 12 Projected LCOE of WSE's WEC at various LRs and as a function of cumulative capacity and the 2020 LCOE of other technologies

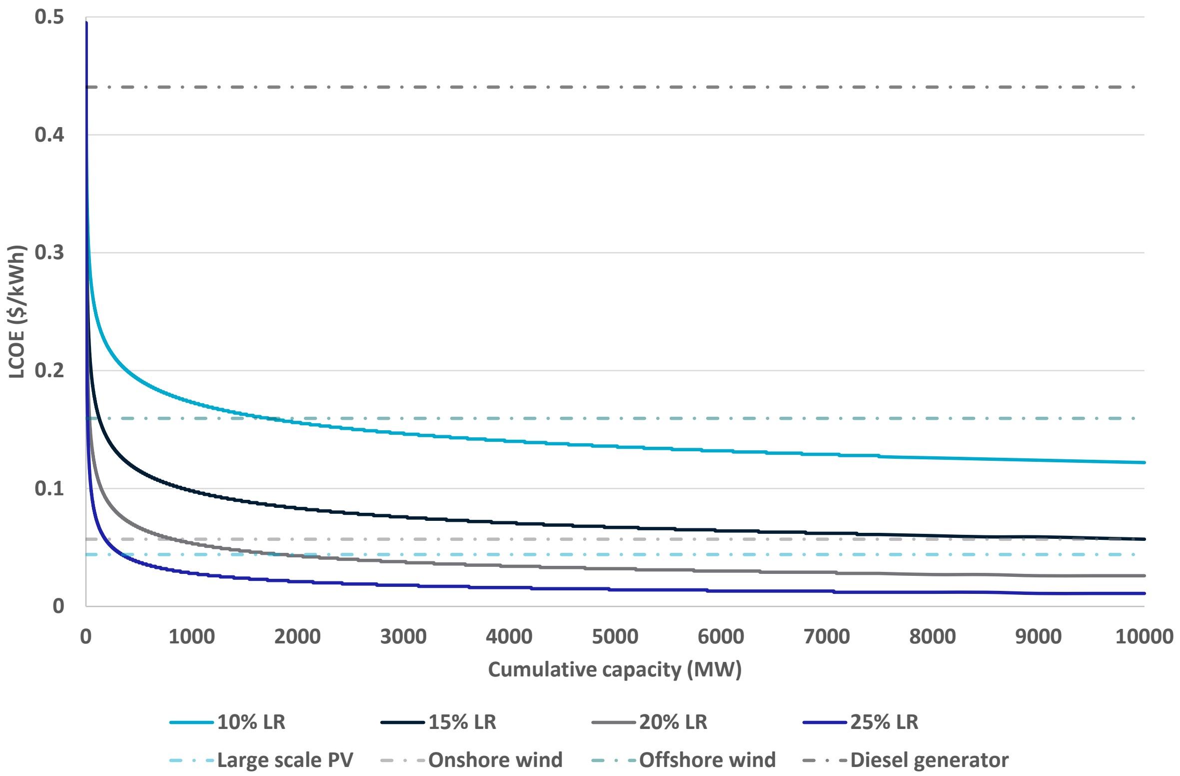

Figure 13 Projected LCOE of WSE's WEC at various LRs and as a function of cumulative capacity and the 2030 LCOE of other technologies

4.4 Sensitivity analysis

The sensitivity of the LCOE to a change of ±25% in each assumption is shown in Figure 14 at 10 MW of cumulative capacity and Figure 15 at 1,000 MW of cumulative capacity. The base value of each assumption is presented with the labels.

At 10 MW of cumulative capacity the capacity factor has the greatest influence on the LCOE, where a 25% increase in capacity factor reduces the LCOE by 20% and a 25% decrease in capacity factor increases the LCOE by 34%. While the impact of the capacity factor on LCOE is the same at 1,000 MW, the assumption with the greatest influence on LCOE at that capacity is the LR. When the LR of 18.23% is reduced by 25% to 13.67% the capital cost increases from 1,884 $/kW to 3,234 $/kW which is almost double and the LCOE increases by 70%. When the LR is increased by 25% to 22.79%, the capital cost reduces to 1,064 $/kW and the LCOE reduces by 43%.

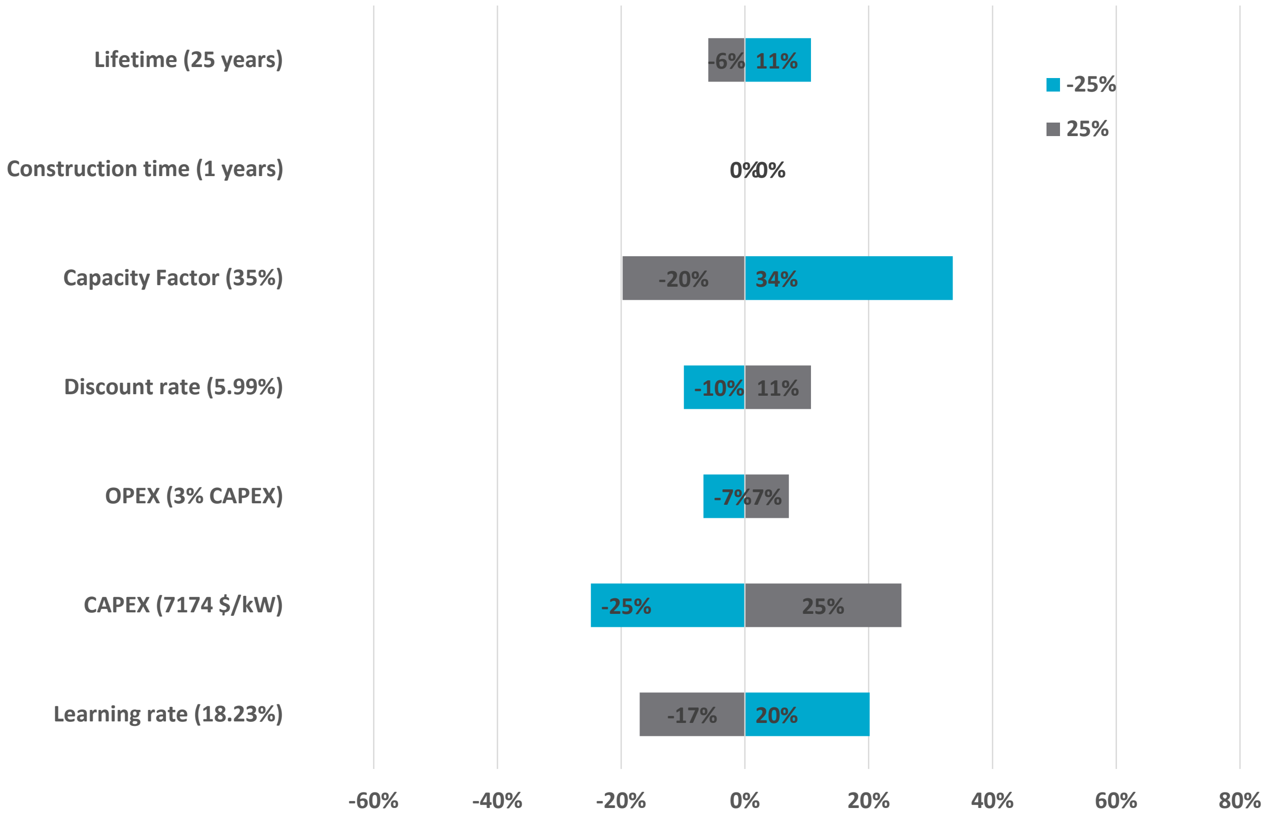

Figure 14 Projected sensitivity of the LCOE to changes in assumptions at 10 MW of cumulative capacity

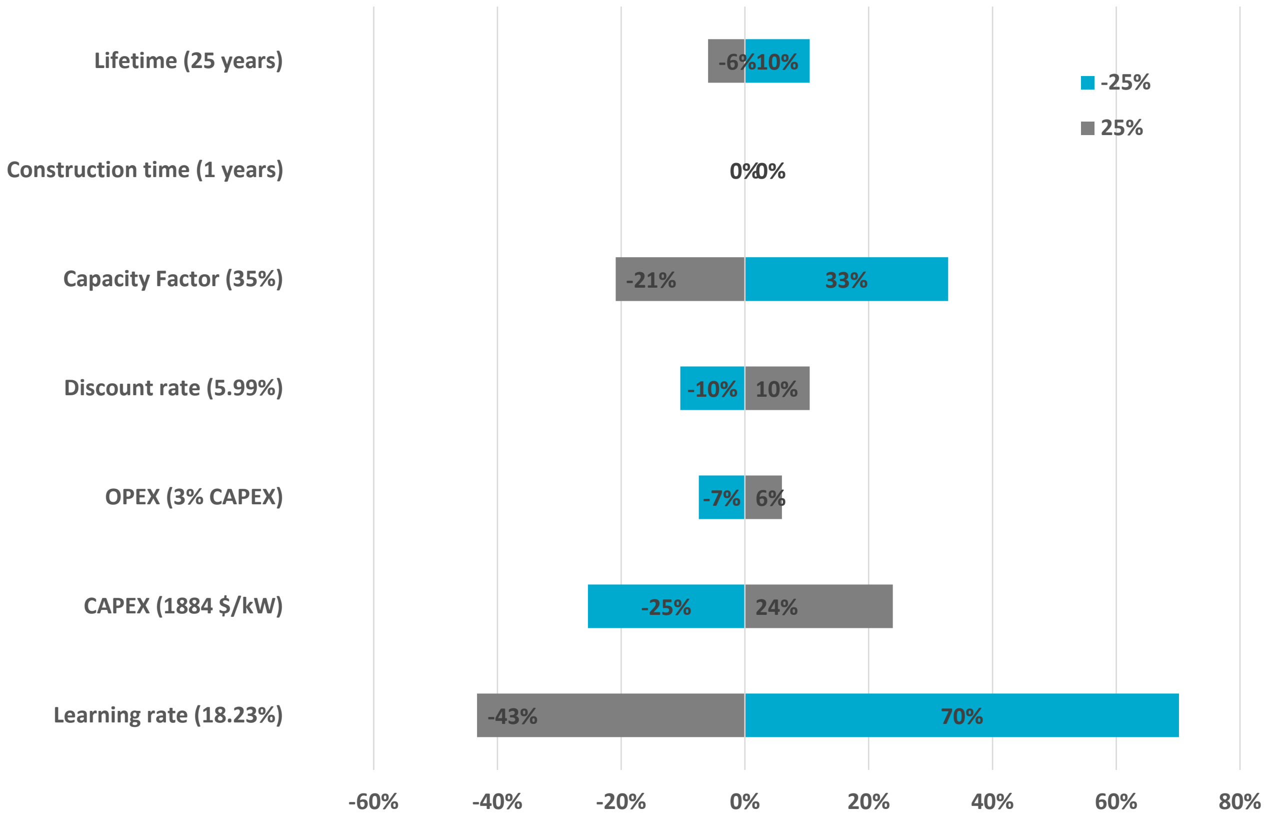

Figure 15 Projected sensitivity of the LCOE to changes in assumptions at 1000 MW of cumulative capacity

4.5 Global electricity sector results

4.5.1 Achievable scenario

The projected global electricity generation mix is shown in Figure 16. From 2021 to 2050, wave energy contributes 11,525 TWh to global electricity generation. To put this into perspective, it is slightly greater than the total contribution of biomass and geothermal generation combined. It also amounts to 718 TWh per annum by 2050, which is more than double Australia's total 2019 electricity generation of 265 TWh. The market share of wave energy in the early part of the next decade is projected to be 0.46%. By 2050, wave energy is projected to achieve a 1.3% global market share, with an LCOE of 0.03 $/kWh and an installed capacity of 170,000 MW.

It should be noted that this scenario is predicated on an immediate uptake of wave energy technology in the form of early projects. A strong "market pull", as described in Section 2.1, is required for the installed capacity of the technology to increase, leading to capital cost and LCOE reductions in line with the above analysis. The reality often experienced by many new energy technologies is that early projects are slower to develop due to caution on the part of funders and other stakeholders. If this cautious slower uptake were to occur in the early phase of the commercialisation of wave energy technology, the above estimate of market share and LCOE by early next decade might be delayed.

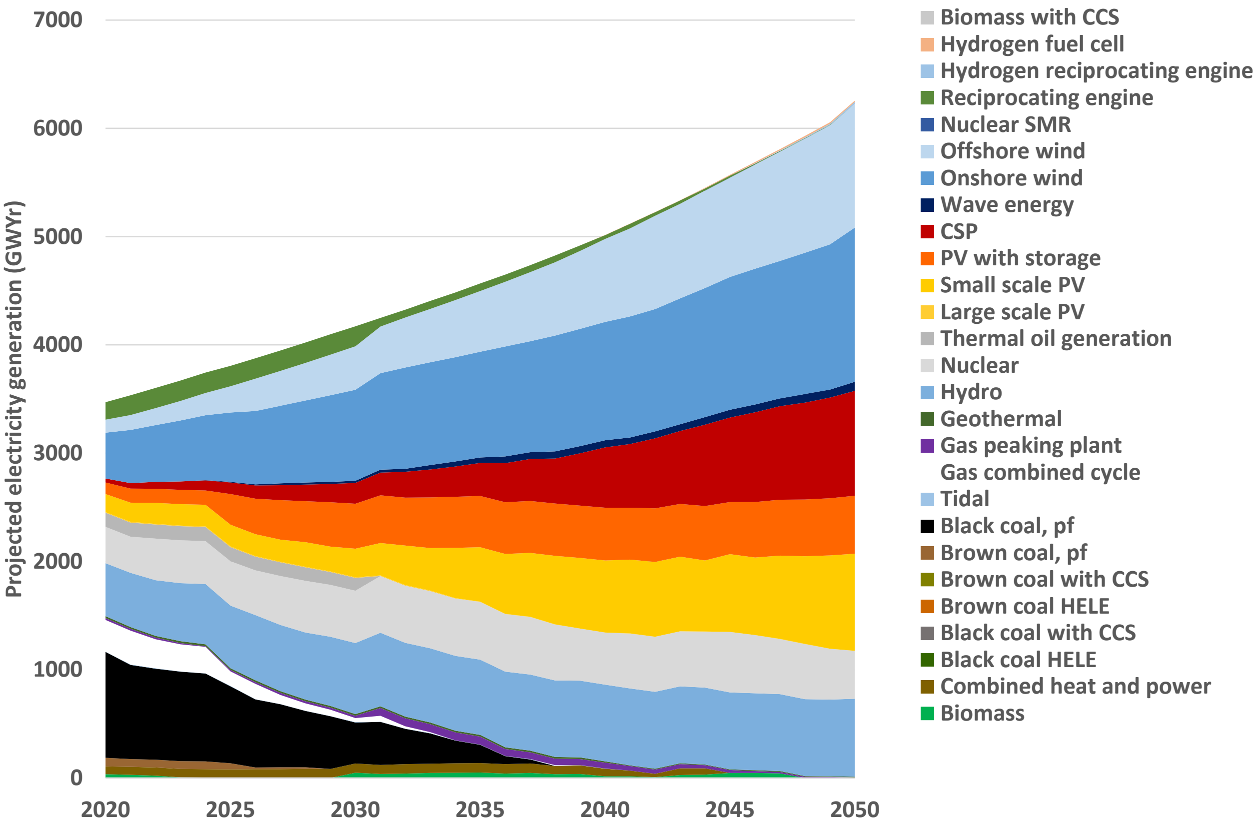

Figure 16 Projected global electricity generation under the Achievable scenario

CCS=Carbon Capture and Storage, SMR=Small Modular Reactor, CSP=Concentrating Solar Power, pf=pulverised fuel, HELE=High Efficiency Low Emission

The majority of wave energy electricity generation is projected to be in North America, which can be seen in Figure 17. Wave energy reaches a 5% market share in North America in 2033 with an installed capacity of 29 GW and an annual electricity generation of 113 TWh. From this point onwards, wave energy can be considered to be out of the early learning stage and into the intermediate stage in North America. Wave energy's 2050 market share is projected to be 8% of total generation.

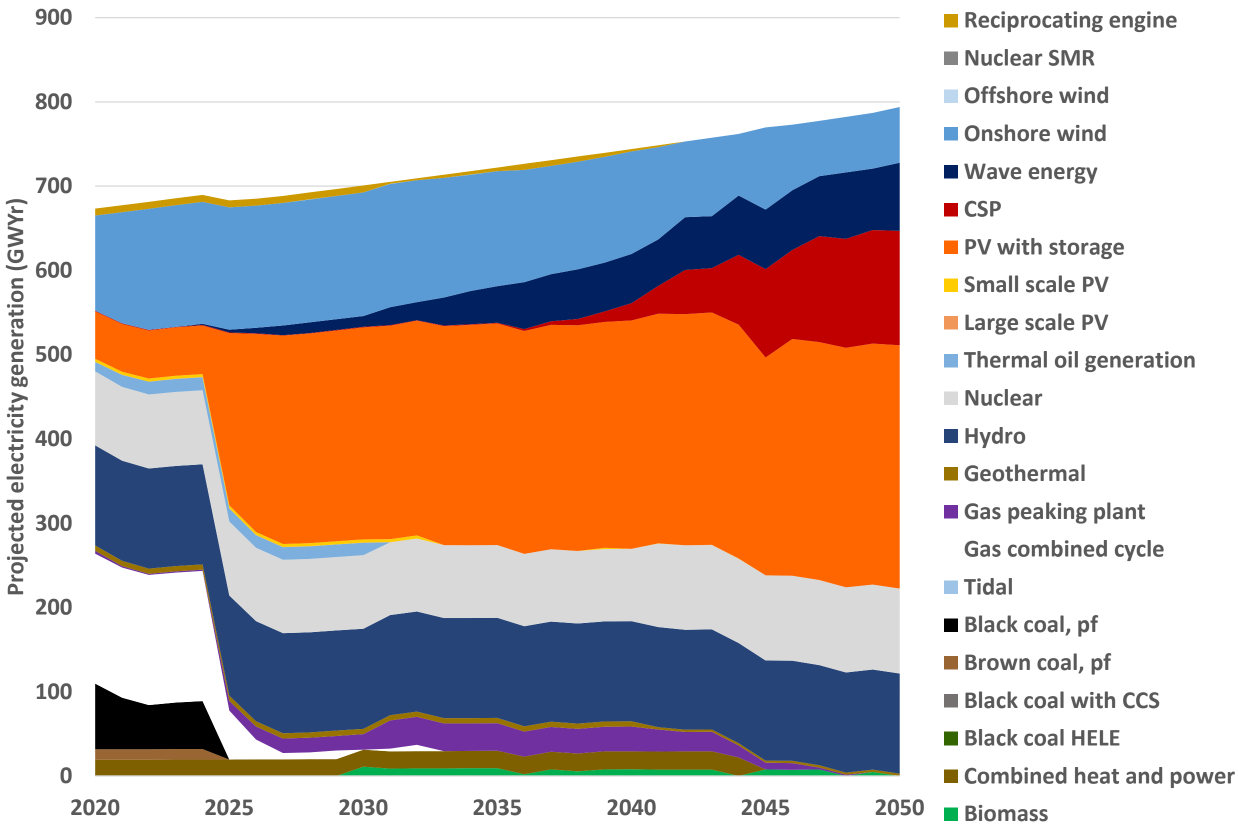

Figure 17 Projected North American electricity generation under the Achievable scenario

4.5.2 Conservative scenario

Figure 18 shows the projected global electricity generation mix under the Conservative scenario. Between 2021 and 2050, wave energy generates a total of 3,210 TWh. By 2050 wave energy is projected to generate 753 TWh per annum. This is slightly greater than under the Achievable scenario. By the early part of the next decade, the installed capacity of wave energy is projected to be 450 MW. This is lower than in the Achievable scenario, which shows the impact LR has on the uptake of wave energy. The change in LR has led to a slower deployment of wave energy, however, by 2050 the installed capacity is higher under the Conservative scenario at 180,000 MW.

As in the Achievable scenario, the greatest amount of wave energy is projected to be installed in North America, as shown in Figure 19. The total generated from 2021 to 2050 is 2,992 TWh. Wave energy reaches a 5% market share by 2046 and by 2050 wave energy's share of generation is projected to be 9%.

The reason wave energy has a 1% higher market share by 2050 under the Conservative scenario is because the installed capacity is slightly higher. This shows that even though the LR was reduced, the additional early supported capacity has led to an increase in the total installed capacity of wave energy by 2050.

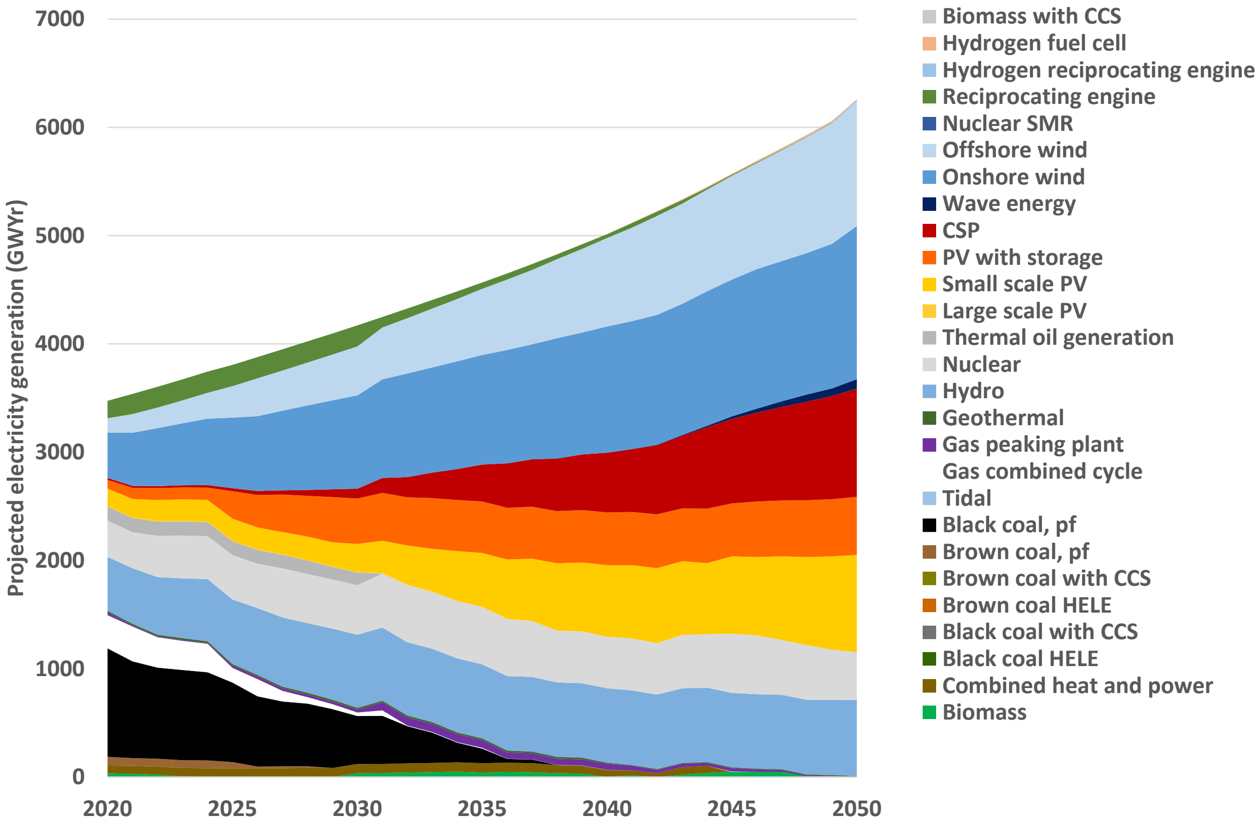

Figure 18 Projected global electricity generation under the Conservative scenario

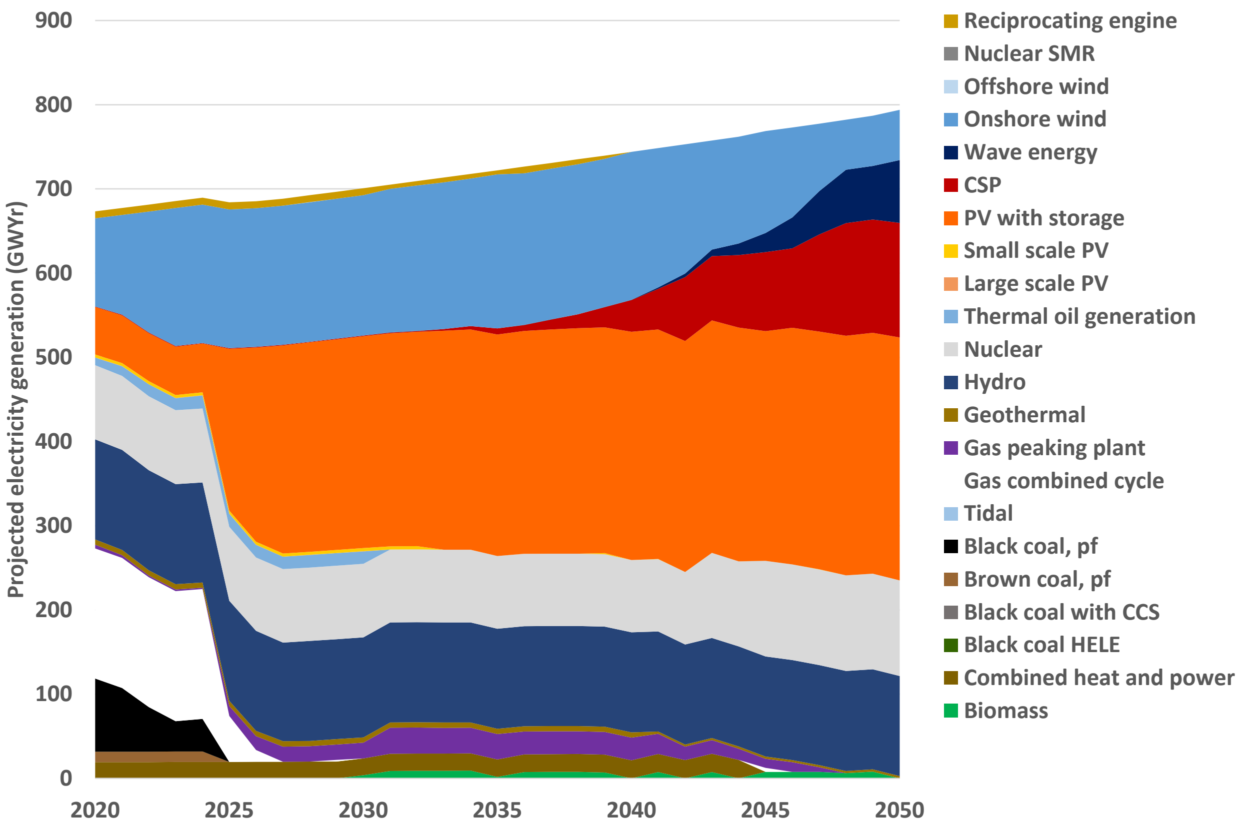

Figure 19 Projected North American electricity generation under the Conservative scenario

4.5.3 LCOE comparison

The modelled capital cost trajectories, and the LCOEs calculated based on those trajectories, and the current LCOE of other technologies, is shown in Figure 20. As can be seen, the flat sections of the graph represent an initial commercial development period, where early-stage projects are being originated, negotiated, and funded. If this phase were to be delayed for any meaningful period of time, the result would be an equivalent translation of the curves to the right on the timeline. And in fact, the Conservative scenario is slightly delayed compared to the Achievable scenario, even though it has more supported deployment. The supported deployment leads to continued, but slower, cost reductions compared to the Achievable scenario. This figure illustrates the difference the change in LR makes to the final outcome.

Therefore, the focus needs to be on maintaining that high learning rate through increased deployment, economies of scale in individual units, farms, and manufacturing. However, even if the learning rate does halve after a cumulative capacity of 20,000 MW, the LCOE of wave energy is competitive against diesel generation in remote locations by 2025 and with offshore wind before 2035.

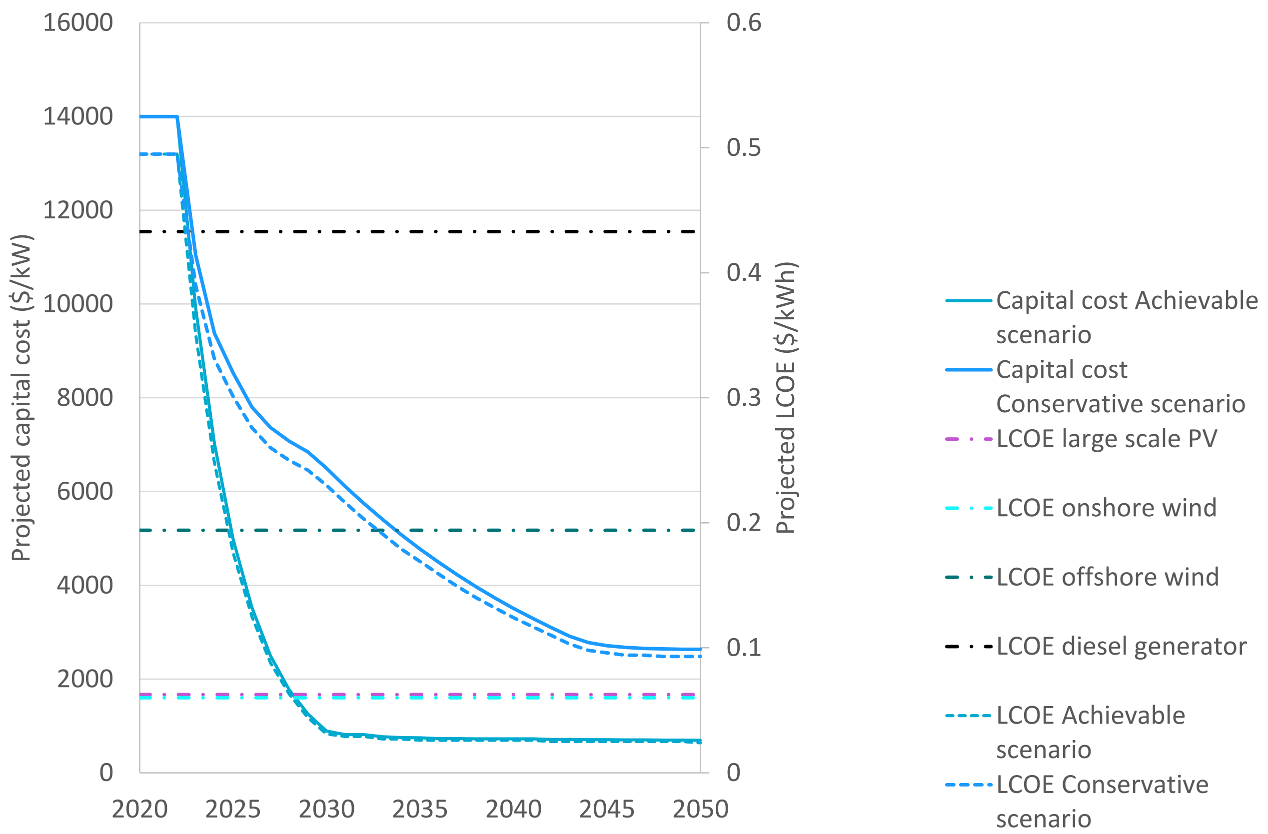

Figure 20 Projected modelled capital cost and LCOEs under the Achievable and Conservative scenarios

5 Discussion

The principle of learning-by-doing, where technological costs have been observed to reduce by a constant factor, known as the LR, as deployment increases, can be used to project future cost reductions. LRs can be calculated at the individual firm level, up to technologies deployed on a global scale. The overwhelming majority of literature LRs are for whole technologies at an industry wide national or global level.

A review of technological development, with a focus on early-stage technologies, has shown that these technologies have an industry wide LR of approximately 20% until they reach approximately 5% market share, at which stage their LR reduces. WSE's technology is currently in the commercialisation phase, which means it is an early-stage technology and thus should have a high LR. Data supporting an individual firm learning rate was not available. An industry wide 18.23% LR was determined from a bottom-up engineering-based calculation using component LRs associated with the offshore wind industry combined with WSE cost data.

The WSE technology currently has an LCOE that is already almost at parity with that of diesel generation in remote locations. This means that WSE's WEC has the potential to readily offset diesel CO_2 emissions and provide electricity at approximately the same cost to island communities that are reliant on expensive diesel, if projects have access to energetic wave resources, such as exist in many locations throughout the world.

If WSE as an individual firm can achieve an LR equivalent to the industry calculated value, the technology is projected to reach cost parity with the 2020 LCOE of offshore wind in Australia after a cumulative capacity of 25 MW and with the 2030 LCOE of offshore wind in Australia once the cumulative capacity has reached 50 MW. Relative to the global average LCOE of offshore wind, these capacities correspond to 45[4]MW and 300[5]MW.

For WSE's WEC to be competitive with solar PV and onshore wind in terms of LCOE, the technology needs to see cumulative installations of 5,543 MW and 1,658 MW by 2030 respectively, while maintaining the industry wide 18.23% LR. In order for WSE and wave energy to reach high levels of installed capacity at that LR, the wave energy sector as a whole will need to cooperate to share knowledge, and be supported through investments and research support which all contributes to cost reductions through learning by doing.

Global electricity sector modelling under the Achievable scenario has revealed that wave energy is projected to have an installed capacity of 42.6 GW by as early as 2030, given a strong early market pull. This is more than what is required to be competitive against large scale solar PV and onshore wind. The timing of these projections relies on the commercialisation of the technology commencing in the near term. A slower uptake will delay the timing. Under the Conservative

[4] Based on a global average offshore wind LCOE of 0.1150 USD 2019/kWh (IRENA, 2020)

[5] Based on a 2030 projected global average offshore wind LCOE of 0.07 USD 2018/kWh (IRENA, 2019)

scenario, which has a reduced LR, large-scale uptake of wave energy is delayed by more than 10 years. However, it reaches a similar installed capacity to the Achievable scenario by 2050.

The global installed capacity of wind and solar energy reached 733 GW and 716 GW respectively at the end of 2020 (IRENA, 2021). Solar PV modules have maintained a high LR of 25% over their 40-year commercialisation phase (Fraunhofer ISE, 2021) and, because of this, has achieved cost reductions to allow them to reach an LCOE of approximately 0.05 $/kWh in Australia (Graham et al., 2020). The capacity factor of solar PV is lower than that of wave energy, which means that wave energy can obtain an equivalently low LCOE at a higher relative capital cost and a lower cumulative capacity than solar PV.

The two largest drivers of the LCOE are the LR (and hence capital cost) and the capacity factor. The impact of the LR increases as cumulative capacity increases because a higher LR results in more significant capital cost reductions as shown by Figure 12 and Figure 13.

The capacity factor has a constant impact on the LCOE, as shown by the sensitivity analysis, where an increase of 25% results in a decrease in the LCOE of 20-21% and a 25% decrease in capacity factor results in a 33-34% increase in LCOE.

These results mean that, to achieve a high level of cost reductions in LCOE terms, the focus needs to be on maintaining the LR through learning by doing, economies of scale in manufacturing, and in installation. At the same time, sites with suitable wave energy resources need to be chosen for projects, and improvements to the technology to increase the efficiency of conversion and, thus, the capacity factor, need to continue to occur.

The analysis in this report is based solely on reductions in capital cost. It does not take into account potential improvements in the conversion efficiency of the technology and, thus, increases in the capacity factor. Technology improvements and increases in capacity factor are inevitable and will lead to an even lower LCOE than those stated in this report.

Appendix A Further information on GALLM-E

GALLM-E has been developed by CSIRO to project the capital cost and uptake of electricity generation technologies. GALLM-E is solved as a mixed integer linear program in which total costs of electricity supply are minimised to reach a given level of electricity demand over time. The model features endogenous technological learning through the use of learning curves at both the global and local scale. The learning curves are segmented into step functions and the location on each learning curve (i.e. cost vs. cumulative capacity) is determined at each time step. The learning curve solution space is non-convex, which means that there are singularities i.e. the solution space is not continuous. However, it is possible to find an optimal, least-cost solution. It also means that any change in any of the parameters that impact the learning curve, such as a change in generation capacity, will result in an entirely new solution space.

GALLM-E has 13 regions based on OECD regional definitions but also some greater resolution of countries that are Australia's main trading partners, namely Australia, Africa, China, Eastern Europe, Western Europe, Former Soviet Union, India, Japan, Latin America, the Middle East, North America, OECD Asia Pacific (without Australia and Japan) and the rest of Asia. It also features 27 electricity generation and energy storage technologies (Hayward & Graham, 2013; Graham et al., , 2021; Brinsmead et al., 2019). It runs from the year 2006 until 2100, however, results are only reported up until 2050 due to the much greater level of uncertainty in the input assumptions beyond that date.

GALLM-E includes a "penalty constraint", where in any given year, if the new installed capacity of a technology exceeds 1/3 of new demand for capacity, then the cost of that technology will increase. If it exceeds 2/3 of new demand for capacity, the cost penalty is even higher. This constraint is based on supply constraints that have been seen in the past for technologies such as wind and PV, where the price increased as demand increased. The constraint ensures that the model recognises the potential to overheat a technology supply chain, and to some extent this constraint encourages a wide variety of technologies to be deployed. However, if it needs to build more of only one technology, it is not prevented from doing so. Similarly, GALLM-E has a market constraint, where again, in any given year new capacity of a technology cannot exceed the existing installed capacity by more than 1.55 times, except for emerging technologies, where this constraint only becomes active after 3 GW of installed capacity. This constraint avoids rapid and unrealistic sudden increases in installed capacity and the value (1.55) is based on the approximate maximum historical build rates of electricity generation technologies.

GALLM-E has constraints on renewable energy resource availability in India, Japan, Asia and Western Europe, based on a review of the literature around technical limits of resources, land availability and roof space availability for rooftop solar PV (Hayward & Graham, 2017). This means these countries/regions are limited in their ability to rely solely on locally generated renewables for electricity generation and so would benefit from importing hydrogen. China (and the remaining regions in GALLM-E) have unlimited renewable resources (relative to expected electricity demand). There is a limited fossil fuel constraint, where brown coal-fired generation can only be located in a region that contains brown coal (as brown coal is not traded).

Government policies are a key driver of technology uptake in GALLM-E. The main policy lever is a carbon price, but there are country and region-specific technology incentives such as forced capacity construction or renewable energy targets.

Key exogenous data assumptions are presented in Table 5.

Table 5 Key exogenous data assumptions and their sources used in GALLM-E

Electricity demand	IEA for the equivalent scenario	(IEA, 2020)
Fossil fuel prices	IEA for the equivalent scenario	(IEA, 2020)
Biomass and uranium prices	CSIRO Australian National Outlook II	(Brinsmead et al., 2019)
Initial capital costs, operating and maintenance costs and plant fuel efficiencies	From several studies but the majority are from the GenCost project 2020	(Graham et al., 2021) (Aurecon, 2021)
Fossil fuel emission factors	Australian factors for direct and indirect emissions	(CO2CRC, 2015)
Historical installed capacities	Various sources most notably the IEA and the United Nations (UN)	(IEA, 2008) (UN, 2013) (UN, 2014)
Government policies	Various sources, majority from the IEA	(IEA, 2020)

Appendix B Brief description of the WSE technology

WSE's WEC generates electricity in a multi-stage process which provides it with ample room for improving the conversion efficiency and, hence, increasing the capacity factor[6], which improves the technology's economics:

- The energy in the incoming wave is converted into an oscillatory column of water
- The energy from the oscillatory column of water is converted into an airflow
- The airflow is converted into mechanical energy via a turbine
- The mechanical energy is then converted into usable electrical energy via various power systems

The geometry of the device is an important factor in determining its performance. The current version of the WEC is made predominantly from concrete and steel, but there are opportunities to use all manner of materials, including composites and recycled plastics that could significantly improve the manufacturing process and hence costs. The WEC can also be tethered to the seabed by various means.

[6] Capacity factor is unitless and is defined as the ratio of electricity generated over a period of time to the maximum possible output i.e. if the plant was operating at its rated capacity continuously.

Shortened forms

ABBREVIATION	MEANING
AEMO	Australian Energy Market Operator
AUD	Australian dollars
CAPEX	Capital Cost
Capfac	Capacity factor
CCS	Carbon Capture and Storage
CO_2	Carbon dioxide
CO2CRC	CO2 Cooperative Research Centre
CRI	Commercial Readiness Index
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSP	Concentrating Solar Power
EU	European Union
EUR	Euro
GALLM-E	Global and Local Learning Model - Electricity
GEA	Global Energy Assessment
GW	Gigawatt
HELE	High Efficiency Low Emission
HVDC	High Voltage Direct Current
IDC	Interest During Construction
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
ISE	Institute for Solar Energy
kW	Kilowatt
kWh	Kilowatt hours
L	Litre
LA	Louisiana
LCOE	Levelised Cost of Electricity
LR	LR
MW	Megawatts
NY	New York
O&M	Operations and Maintenance
$O\&M_{FIX}$	Fixed Operations and Maintenance
$O\&M_{VAR}$	Variable Operations and Maintenance
OECD	Organisation for Economic Co-operation and Development
OPEX	Operations and Maintenance Cost

OWC	Oscillating water column
pf	Pulverised fuel
PV	Photovoltaics
R&D	Research and Development
SMR	Small Modular Reactor
TRL	Technical Readiness Level
TWh	Terrawatt hours
UK	United Kingdom
UN	United Nations
USA	United States of America
USD	United States Dollar
WACC	Weighted Average Cost of Capital
WEC	Wave Energy Converter
WSE	Wave Swell Energy

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