Final Report

Hydrogen Capital Cost Reduction Study

ARENA

2026

worley consulting

Executive Summary

Executive Summary

This study identifies 24 independent initiatives that combine to reduce project capital costs

Context and Basis

ARENA commissioned Worley Consulting to better understand capital costs for large-scale green hydrogen production projects in Australia, focusing on achievable long-term cost reduction pathways rather than point forecasts. The study analysed key cost drivers and identified opportunities to reduce costs through technological improvements and optimised design, procurement and construction approaches. The findings are intended to inform industry on cost reduction approaches, guide ARENA's investment and assessment decisions, and support government policy development.

The study created four reference estimates based on three prevalent electrolysis technologies. These included proton exchange membrane (PEM), alkaline water electrolysis (AWE) and solid oxide electrolysis cells (SOEC). Details of the reference estimates are below:

Reference Project (RP)	RP1	RP2	RP3	RP4
Description	100 MW SOEC, VIC	1,000 MW PEM, SA	1,000 MW AWE, SA	10,000 MW PEM, WA
2025 reference estimate (AUD/kWe)	7,250	5,270	4,770	4,810

The basis for the reference estimates incorporates two factors that are relatively conservative compared with other benchmarks. This basis was created to allow quantification of the effect of these in future cost reduction forecasts. These are:

1. a relatively high electrolyser purchase price, reflecting procurement from Western suppliers (such as European or US-based manufacturers), and
2. the inclusion of contingency allowances to reflect the nascent state of the renewable hydrogen sector.

General findings on capital cost

There are **multiple credible avenues** for cost-reduction of renewable hydrogen production projects in Australia. This study provides details of **24 independent 'cost-out levers'** that each reduce project capital cost.

The levers were **each quantified** using a balance of **credible public information**, and **Worley's own expertise**. The results are a probabilistic combination of **correlated, exclusive** and **independent** cost reduction potential of each lever in 2035, and in 2050.

If development keeps pace with projections, then this study found:

- **Project developers** have carriage of most of the immediate savings, aggregating to **68% of the reductions by 2035**, and **58% by 2050**.
- By bringing advanced project delivery practices in **digitalisation, lean construction, scope and specification minimisation,** and **project standardisation** developers could implement initiatives that could be **effective starting today**. This would result in an average of more than 20% reduction by 2035, and more than 25% by 2050.
- **Equipment modularisation** enables savings in other areas: **logistical efficiency**, **simpler construction** and **project standardisation** combine to yield 18% reduction from todays prices by 2035, and 21% in 2050 across all reference technologies, on average.

These high-level findings can be combined, and the effects of this are presented on the following page.

Executive Summary

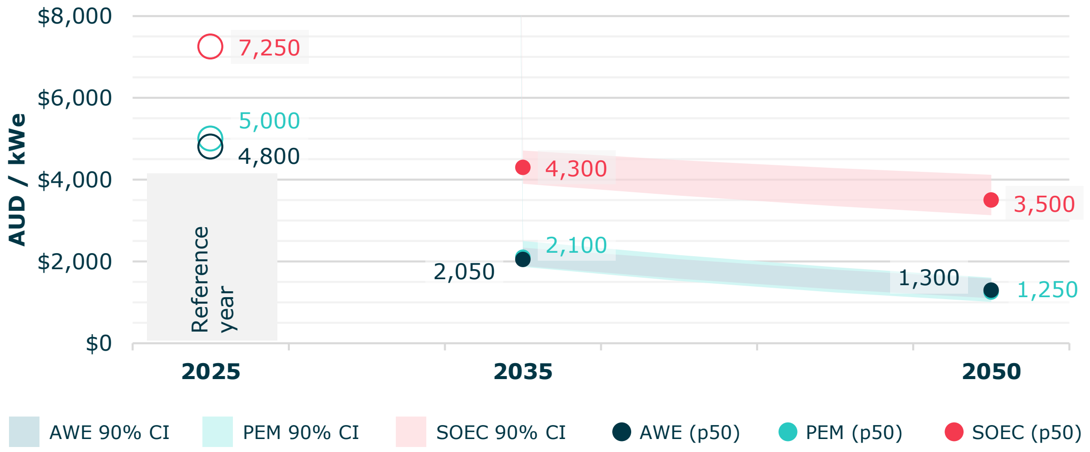
Capital costs for prevalent technologies could fall by between 55 and 60% by 2035 and up to 80% by 2050 compared to today's estimates

Hydrogen production technology findings

Estimates for the most prevalent electrolysis technologies (PEM and AWE) are predicted to reduce to a 90% confidence interval (CI) between **1,870 and 2,500 AUD/kWe by 2035** and between **1,010 and 1,600 AUD/kWe by 2050**.

Costs for solid oxide electrolysis cell (SOEC) technology are expected to **reduce to between 3,900 and 4,710 AUD/kWe** (41%) in the central case by 2035 and between **3,130 and 4,120 AUD/kWe** (52%) in 2050.

Details are available in the figure below:



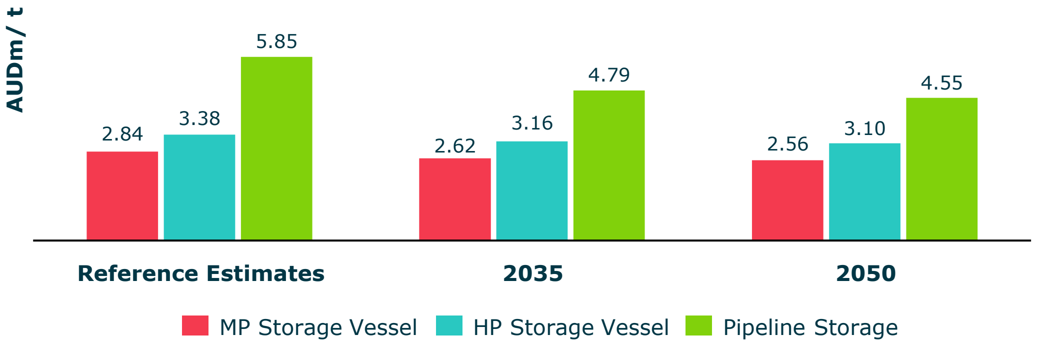
Hydrogen Gas Storage and Compression findings

Hydrogen gas storage is an investment for a lower unit cost of hydrogen. This study assessed three storage technologies on a common basis, and they add between **16 and 32% of project capital**.

Medium pressure (**MP**) **storage vessels** are consistently the lowest cost option and reach **2.56 AUDm/t by 2050**.

Most potential capital cost reduction is for gas storage in pipelines – which could see costs reduce by 22% in the central scenario by 2050. This prediction relies primarily on **improvements in construction labour productivity** and **developments in pipeline metallurgy**.

Details are available in the figure below:



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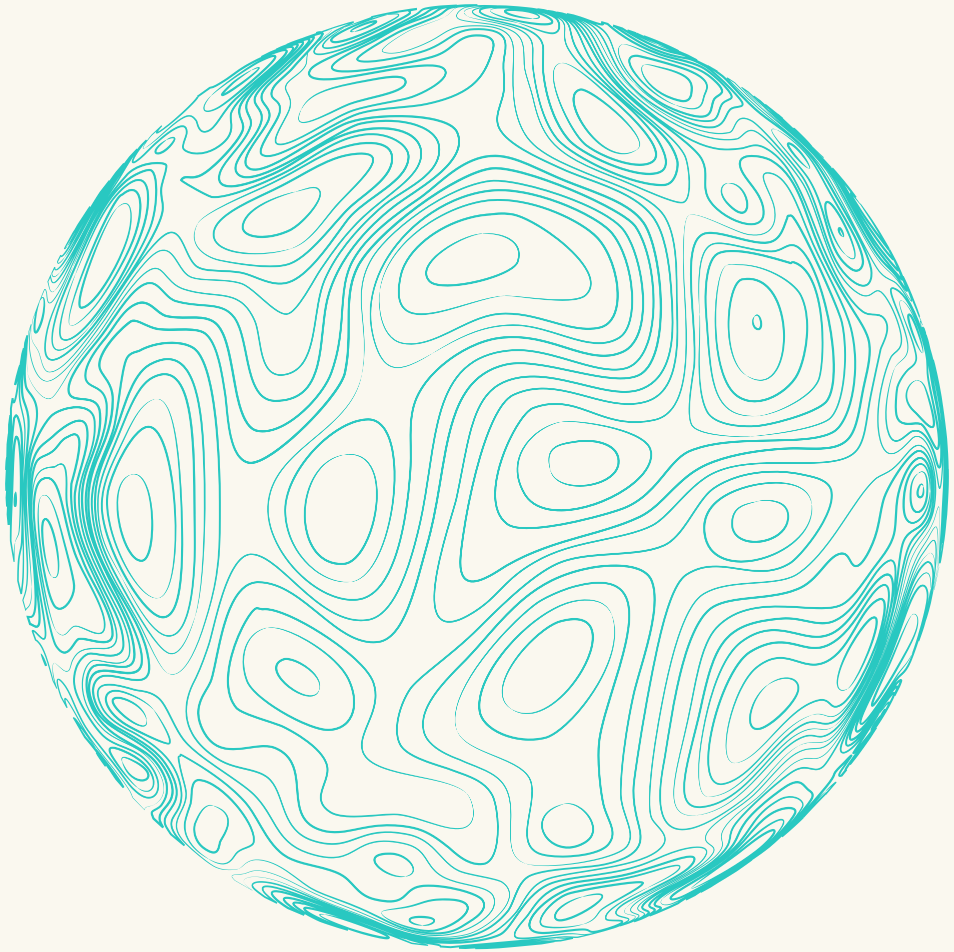
Context and Scope



Context and Scope

This study assesses capital cost reductions for renewable hydrogen production in Australia

1.1 Introduction

Renewable hydrogen produced by electrolysis is considered a critical decarbonisation tool for hard-to-abate industries. Despite heightened interest from industry and government, and considerable investment, the rate of renewable hydrogen adoption significantly lags early expectations.

A leading commercial challenge is the high capital cost of hydrogen production projects. Cost reduction in the long-term is expected, and this contrasts with cost increases in the years since 2020. These cost increases have been ascribed various explanations (such as increased global inflation, slower than expected energy transition and/or other transient macro-economic trends).

This report presents the grounding elements to identify solutions to invert such cost trend by defining cost estimates for renewable hydrogen project archetypes, and a list of cost reduction concepts that apply to these production technologies.

This study seeks to transparently link capital costs for renewable hydrogen facilities today, to future cost reductions. This study will present capital cost estimates for relevant project configurations in Australia, then use these configurations to quantify avenues of future cost reduction.

The information and analysis from this report is intended to inform:

- Policy makers by identifying risks and incentives that government could play a role in underwriting,
- Decision makers in making informed judgements on the relative merits of hydrogen as part of the energy transition, alongside total costs of production,
- Supporting Developers create a design and development approach in conjunction with their business case for hydrogen projects,
- Developers in identifying areas that would benefit from additional focus through research attention.

This report presents the following content to aid in transparent and informed dialogue:

- The scope of the assessments considered, in Chapter 1
- a basis for the study, and for the estimates presented, in Chapter 5,
- a series of reference project estimates, in Chapter 6, and
- a description of cost reduction initiatives 'Cost-out Levers' in Chapter 7

The authors caution that when comparing costs, it is important to understand how cost estimates are derived and their purpose. There are many studies which provide valuable information regarding the comparative costs of hydrogen production technologies and the factors that impact these costs.

General studies are typically poor predictors of costs for specific projects because they may not accurately account for the variation in project specifics, site and owner requirements included in a real-world project cost estimate. Similarly, costs incurred for specific projects can be poor representations of costs for the technology at large, or for use in wider comparisons. This study seeks to reconcile both methods by examining four distinct archetypes, based on actual commercial quotes and recent implemented experience.

Context and Scope

This study considers a range of relevant technologies, scales and locations

1.2 Scope

Renewable hydrogen can be produced in a variety of commercial and physical configurations. This study presents capital cost estimates for renewable hydrogen production by electrolysis and excludes costs for electricity generation, water supply and hydrogen transport.

This report contains:

- The definition of four hydrogen reference project configurations across a range of locations intended to be relevant in the Australian market now, and out to 2050,
- Total Installed Cost (TIC) estimates for the four reference projects to a transparent estimate breakdown structure, and their basis,
- The definition of three relevant hydrogen storage technologies that could enable hydrogen supply buffering from the dynamic operation of a renewable hydrogen facility,
- TIC estimates for the three hydrogen storage technologies,
- A list of initiatives, called 'Cost-out Levers', that are expected to reduce capital costs now, and in the future. These cost-out levers are mapped to the same breakdown structure of estimates for both reference project configurations, and hydrogen storage.

This report presents a quantified combination of the reference project costs with the cost-out levers. This is the result of probabilistic modelling and forms the basis for installed green hydrogen capex cost forecasts in 2035 and 2050.

The estimates in this report, therefore, represent current and future cost estimates presented in AUD per kilowatt electrolysis installed (kWe) for hydrogen production.

All estimates are of project-only costs, and exclude costs of finance, costs of operation and short-term supply chain impacts and other macroeconomic trends, such as foreign exchange fluctuation. Trends that could increase costs are also not explicitly addressed (such as increasing value of precious metals) where they are not relevant to cost-out levers.

Authors are aware of a price divide for primary electrolyser equipment between western (mainly the USA and Europe) and eastern (predominantly Chinese) countries of origin and the impact of this divide is one of the Cost-out Levers.

To address this divide, this study created reference project estimates based on Western supplier pricing, which is known to be a relatively high starting reference estimate (refer to Chapter 6). The relative impact of procuring comparable, cheaper technology is the basis of a cost-out lever (Chapter 7).

This study creates reference projects for assessment which cover a range of technology, scale and location:

- The technologies considered are:
  - proton exchange membrane (PEM) water electrolysis,
  - alkaline water electrolysis (AWE), and
  - electrolysis in a solid oxide electrolysis cell (SOEC).
- The scale of reference projects range between 100 MWe and 10,000 MWe
- Locations are a subset of locations relevant to hydrogen production in Australia, and span Victoria, South Australia and Western Australia.

Context and Scope

This study defines a general hydrogen production facility for assessment

1.2 Scope

Figure 1-1 is a systems diagram that represents a generalised green hydrogen production facility (HPF) adopted for this study, which includes the following:

- Electrical infrastructure - high voltage (HV) switchgear, substation and associated transformers and rectifiers,
- A battery energy storage system (BESS) which provides grid stability support and standby power, and is not for hydrogen production,
- Demineralised water treatment for water supply to electrolysis,
- Hydrogen production and gas purification by electrolysers and associated hydrogen purification equipment,
- Hydrogen product compression where required,
- Waste heat recovery unit (WHRU) and steam system (SOEC only), and
- Supporting utilities and infrastructure – instrument air, nitrogen, cooling, wastewater treatment, etc.; and e.g. buildings.

Chapter 8 presents a basis for product hydrogen storage and compression, and subsequent analysis. The equipment includes:

- Hydrogen storage, and
- Storage compression

Details of the basis of this study are in Chapter 5, and details of the reference project estimates are in Chapter 6.

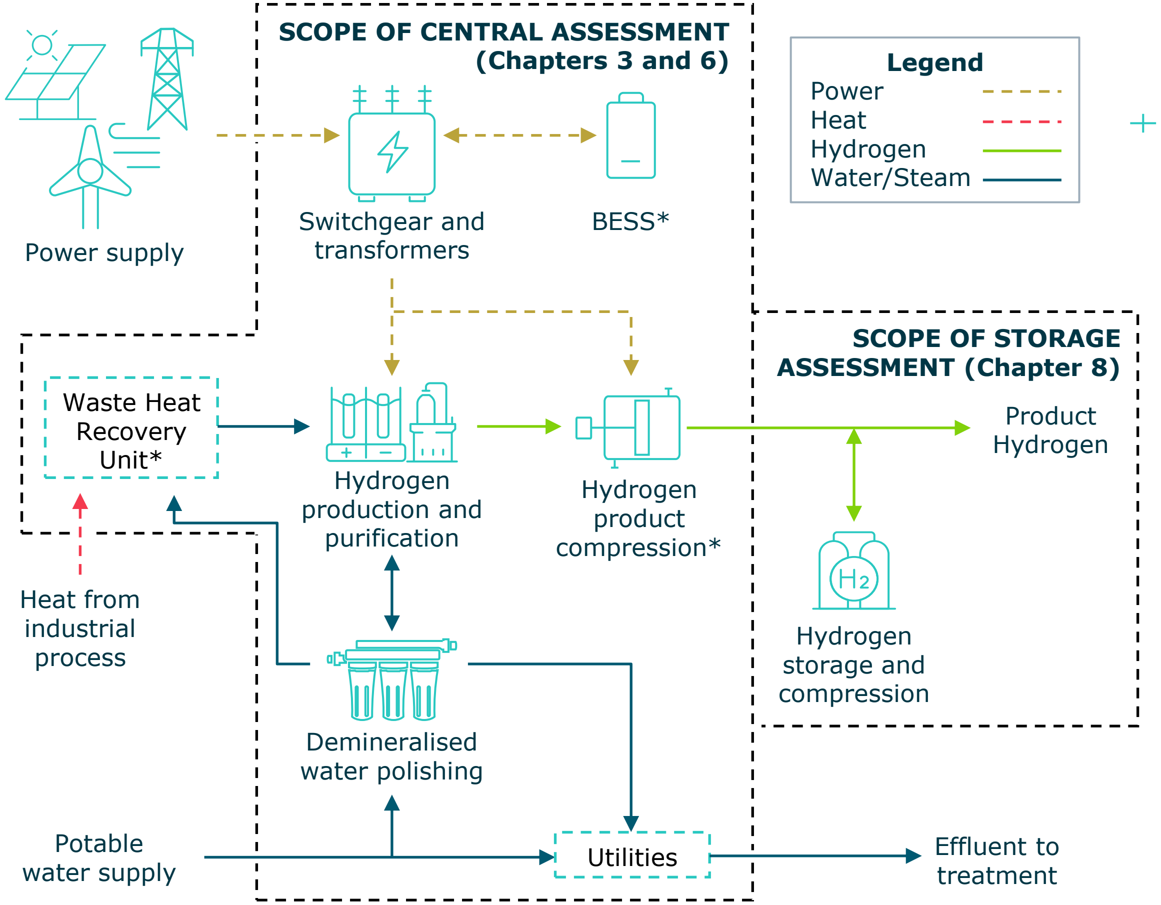


Figure 1-1: General reference project configuration

**Equipment relevant only to a subset of reference projects. Details of reference projects are available in Chapter 5.*

Context and Scope

Breakthroughs in electrolysis technology hold potential, estimates of likelihood are broad

Special topic: breakthrough electrolysis technologies

Hydrogen electrolysis is dominated at present by alkaline and PEM core technology. Solid Oxide derivatives and other alternative breakthrough technologies are in various stages of readiness. Cost reductions are expected from the development and establishment of breakthrough electrolysis technology that fundamentally change the equipment involved.

Special mention is made in this report of two technologies that both represent relative break throughs when compared to PEM and Alkaline technologies:

Solid Oxide Electrolyser Cells (SOEC)

Solid oxide electrolyser cells are hydrogen electrolysers that operate at elevated temperature. This allows the reaction to overcome some heat of reaction and operate at a higher electrical conversion efficiency. Where possible, this heat can be donated 'over-the-fence' by an industrial neighbour.

This study presents a basis, reference estimates and forecasts of cost reduction. The fact remains that there is more uncertainty around this technology when compared to other technologies in this study.

Capillary fed electrolysis (CFE)

CFE re-configures traditional water electrolysis to maximise surface area for reaction and greatly minimise balance of plant equipment. The technology does this by creating electrolysis cells configured to capture oxygen and hydrogen gas bubbles as they emerge.

Australian developer Hysata has constructed a 200kW facility at Port Kembla in New South Wales, and is now developing a 1MW facility (ARENA, 2026).

Hysata's stated efficiency figures exceeds international 2050 targets of 85%; Hysata advertise an efficiency of 95%; and this will come with reduced balance of stack, and balance of plant costs.

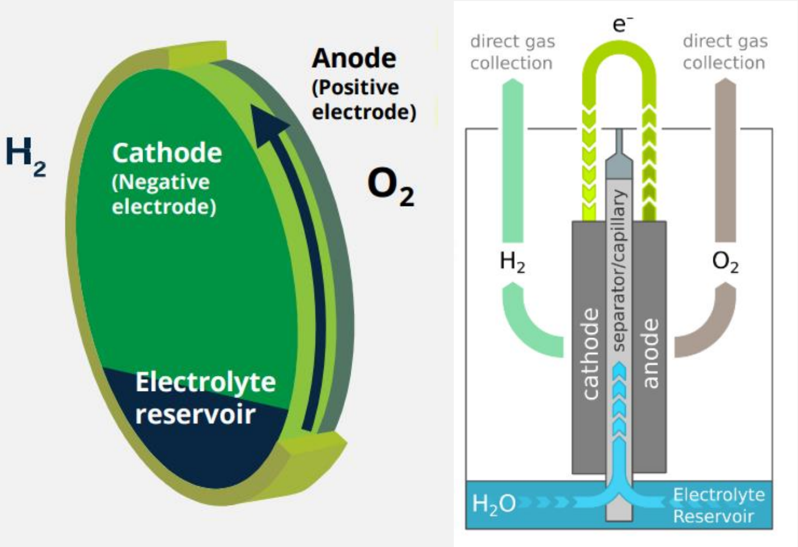


Figure 1-2: Capillary fed electrolysis graphics (*Hysata*)

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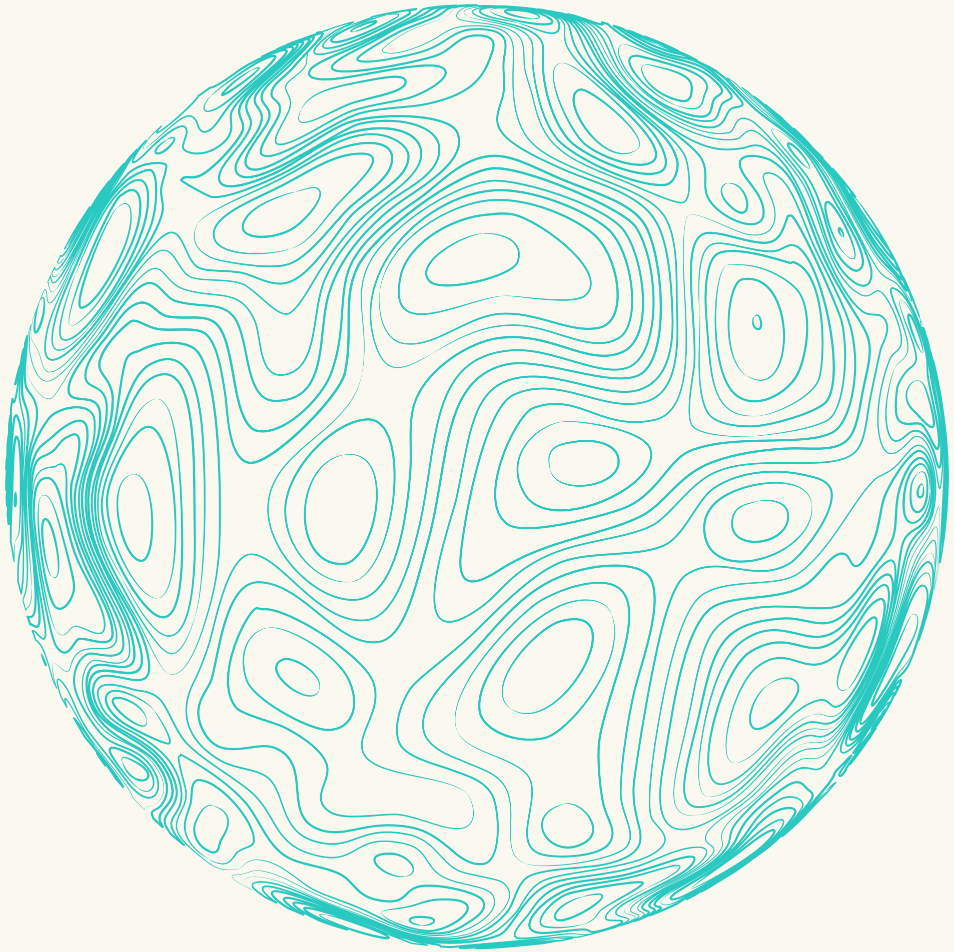
Findings



Findings

Project costs for PEM and AWE are predicted to fall 50-65% by 2035, and 65-80% by 2050.

There are multiple credible avenues for cost-reduction of renewable hydrogen production projects in Australia. This study names and describes **24 independent 'Cost-out Levers'** that each reduce project capital cost. This study then presents a transparent basis for each and predicts cost reductions based on four reference projects. **In all scenarios costs are predicted to reduce** as the industry progressively adds hydrogen production capacity.

- Across the reference project estimates for **PEM and AWE** technologies the TIC are estimated to **reduce by between 50 and 65% by 2035** relative to today. Savings are higher in more optimistic scenarios and deepen to between **65 and 80% by 2050**, Costs are expected to range between 1,010 and 1,600 AUD/kWe by 2050. Refer to Table 2-1 below.
- Costs for **SOEC technology** are expected to **reduce by 41%** in the central case by 2035 and **52% in 2050**, or between 3,130 and 4,120 AUD/kWe. Despite SOEC technology having less deployed capacity, costs for this technology are not projected to reduce by as much the PEM and AWE equivalents. This is primarily because much of the cost is based on mature equipment that is not expected to reduce in cost, or which is limited by the physics of materials subject to high temperature (i.e. heat exchangers, high temperature piping). Recall that the value-proposition of SOEC is higher thermal efficiency - while capital costs remain higher, it is expected to remain relevant when measured on whole-of-life levelised costs.

Table 2-1: 90% confidence interval results in 2025, 2035, and 2050 (AUD/kWe)

Reference projects		2025	2035			2050		
		Reference Estimates	P10		P90	P10		P90
Reference project 1	100 MW SOEC, VIC	7,249	3,900	**4,307**	4,710	3,130	**3,495**	4,120
Reference project 2	1,000 MW PEM, SA	5,274	1,960	**2,176**	2,500	1,080	**1,283**	1,600
Reference project 3	1,000 MW AWE, SA	4,774	1,890	**2,063**	2,340	1,100	**1,285**	1,580
Reference project 4	10,000 MW PEM, WA	4,814	1,870	**2,092**	2,300	1,010	**1,226**	1,440

Findings

76% of the total cost reduction is achievable by 2035, primarily developer-led.

Cost-out Levers were also categorised by the party most responsible for taking action that would result in cost reduction. In the aggregate:

- In 2035, **developers could enact cost-out levers that contribute to around 68%** of the projected savings. OEMs are responsible for most of the remainder (32%).
- **By 2050 OEMs are responsible for a larger fraction than 2035**, around 42% of total savings as technology improvements relatively outweigh developer-led benefits from 2035. Refer to Figure 2-2 to the right.

There are also related items that when performed in concert result in the following predicted possible cost reductions:

- By combining project advanced practices in **digitalisation, lean construction, scope and specification minimisation,** and **project standardisation** developers could reduce costs by 20% compared to today, across all reference technology types.
- The stacking benefits of **modularisation, logistical scale, simplified construction** and **project standardisation** combine to yield 18% saving from today on average in 2035, and 21% in 2050 across all reference technologies.

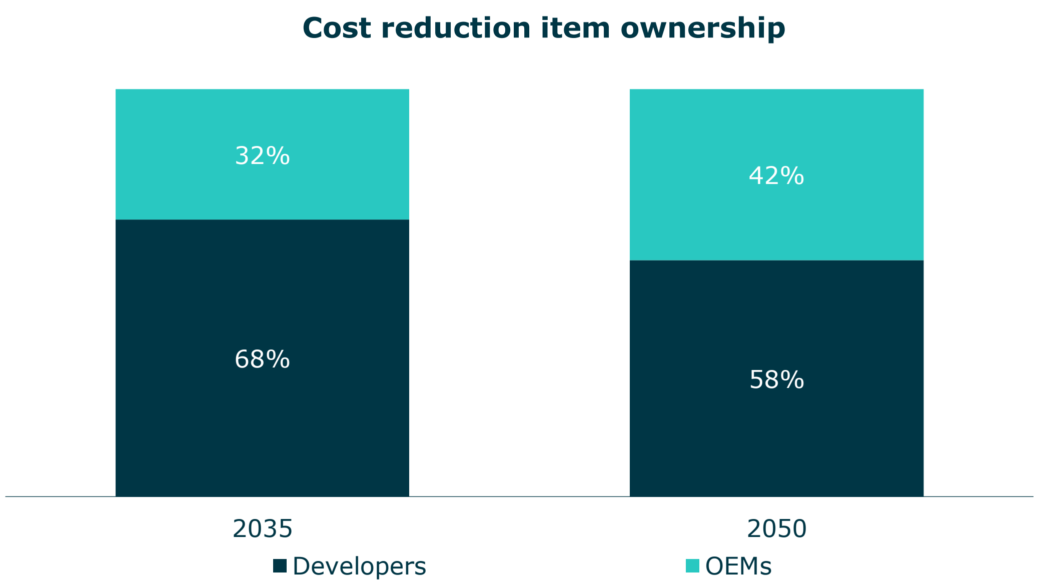


Figure 2-2: Cost reduction proportion for Developer and OEM owned levers

Findings

The most significant eight levers contribute 76% of the total cost reduction by 2035

Table 2-2 shows the projected savings in the outcome. It shows that in the central case:

- 76% of the TIC savings are expected before 2035, and of that 76%, another 76% of those savings arise from the top 8 levers.
- Half of the savings expected in the scenario in the following 15 years from 2035 to 2050 are reliant on one item. The progress on this item has a high range of uncertainty - the item removes grid support equipment from facilities by using advanced rectifier designs relying on insulated-gate bipolar transistors (IGBT). The potential saving relies wholly on the costs for IGBT equipment reducing.
- 80% of the cost reduction potential by 2050 is achieved by 9 out of the 24 cost-out levers.
- 11 of the 24 cost-out levers are predicted to have their full cost reduction potential effective by 2035, with minimal change out to 2050.

Table 2-2: Cost out levers ranked by cost reduction potential (%) for AWE and PEM technologies.

Cost out lever	Cost reduction potential (%)		
	2025-2035	2035-2050	2025-2050
Purchase lowest cost equipment	14%	-	14%
Development maturity and collective industry learning	7%	2%	9%
Low voltage rectifier and control system advancement (insulated-gate bipolar transistors)	-	9%	9%
Electrolyser module scale increase and modular optimisation	5%	4%	8%
Current density advancements	4%	2%	6%
Industrial hub co-location and beneficial use of Common Use Infrastructure	5%	-	5%
BOP optimisation and reduction	3%	1%	4%
Lean construction methods	4%	-	4%
Project-to-project standardisation	2%	-	2%
Remaining items	*14%*	*2%*	*16%*
Total	**57%**	**19%**	**76%**
Proportion of total cost reduction potential by all levers	*76%*	*24%*	-
Proportion of total cost reduction potential by top 9 levers	*76%*	*91%*	***80%***

Findings

Hydrogen storage adds 16-32% to project capital costs

Hydrogen gas storage is an enabler for a lower total cost of hydrogen, and confirming the appropriate scale of hydrogen storage is an optimisation that considers the dynamics of the whole value chain – from electron to end-user. This study estimates that hydrogen gas storage **can add between 16 and 32% of project capital**.

This study assessed three storage technologies on a common basis. This was a 290t storage capacity based on reference project 2, the PEM archetype based in South Australia. Refer to Table 2-3 for Central estimates of storage costs and Chapter 8 for detailed information on the hydrogen storage basis.

1. The scale of capital cost reduction for storage is less than projected cost reductions for hydrogen production facilities.
2. Cost reduction levers identified predict that storage costs could reduce cost by between 7 and 18% in 2035 in the central cases, depending on the technology.
3. The highest cost reduction is identified for pipeline storage, arising from:
   a) labour productivity improvements: where project execution best practice is expected to reduce site labour costs (such as for welding and fitting), and
   b) improvements in material science will reduce costs as risk tolerances are tuned and operational pipelines feed back into leaner design allowances.
3. Capital savings on storage technologies are expected to be reaching a point of diminishing returns in 2035, and by 2050 savings are expected to range to between 10 and 22% of the original storage estimates in the central cases.

Table 2-3: Central estimates of storage costs and reductions in 2035, and 2050 (AUD/kWe)

Storage Option	Reference Estimate		2035		2050	
	AUD/kWe[1]	AUDm/t	AUD/kWe[1]	AUDm/t	AUD/kWe[1]	AUDm/t
MP Vessel Storage	823	2.8	759	2.6	742	2.6
HP Vessel Storage	980	3.4	917	3.2	898	3.1
Pipeline Storage	1,697	5.9	1,388	4.8	1,320	4.6

1. Where values are given in AUD/kWe, these are based on the scale of reference project 2, 1000 MWe.

Findings

Cost for hydrogen storage can reduce by between 16 and 32%, mostly before 2035

The cost reduction potential of each cost-out lever for the hydrogen storage technologies are shown in Table 2-4. Key findings include:

- An average of 80% of the TIC savings across technology types are expected before 2035, the following 15 years responsible for only 20% TIC savings.
- MP and HP storage vessels benefits the most from lean construction methods, achieving 4% and 3% reduction in TIC by 2035, respectively.
- Pipeline storage benefits the most: savings material substitution in piping, vessels and other equipment, achieving 8% reduction in TIC by 2035.

Similar to the hydrogen production infrastructure, TIC savings for hydrogen storage are largely achieved by 2035. The pipeline storage has the greatest TIC cost reduction potential; however, the 2050 TIC of 1,320 AUD/kWe is still significantly higher than both the MP and HP storage vessels.

Table 2-4: Cost out levers by 2050 cost reduction potential (%) for hydrogen storage technologies.

Cost out lever cost reduction potential (%)	MP Storage Vessel			HP Storage Vessel			Pipeline Storage		
	2025-2035	2035-2050	2025-2050	2025-2035	2035-2050	2025-2050	2025-2035	2035-2050	2025-2050
Lean construction methods	4%	-	4%	3%	-	3%	5%	-	5%
Development maturity and collective industry learning	1%	1%	2%	2%	1%	3%	-	-	-
Advanced construction methods reducing field hours	1%	1%	2%	-	1%	1%	2%	4%	5%
Contracting cost reduction	1%	-	1%	1%	-	1%	2%	-	2%
Digitalisation, predictive design and advanced scheduling	1%	-	1%	1%	-	1%	1%	-	1%
Scope minimisation to minimum technical solution (MTS) across all components	-	-	-	-	-	-	1%	-	1%
Material substitution in piping, vessels and other equipment	-	-	-	-	-	-	8%	-	8%
Total	**8%**	**2%**	**10%**	**7%**	**2%**	**8%**	**18%**	**4%**	**22%**
Proportion of total cost reduction potential	*79%*	*21%*	-	*78%*	*22%*	-	*82%*	*18%*	-

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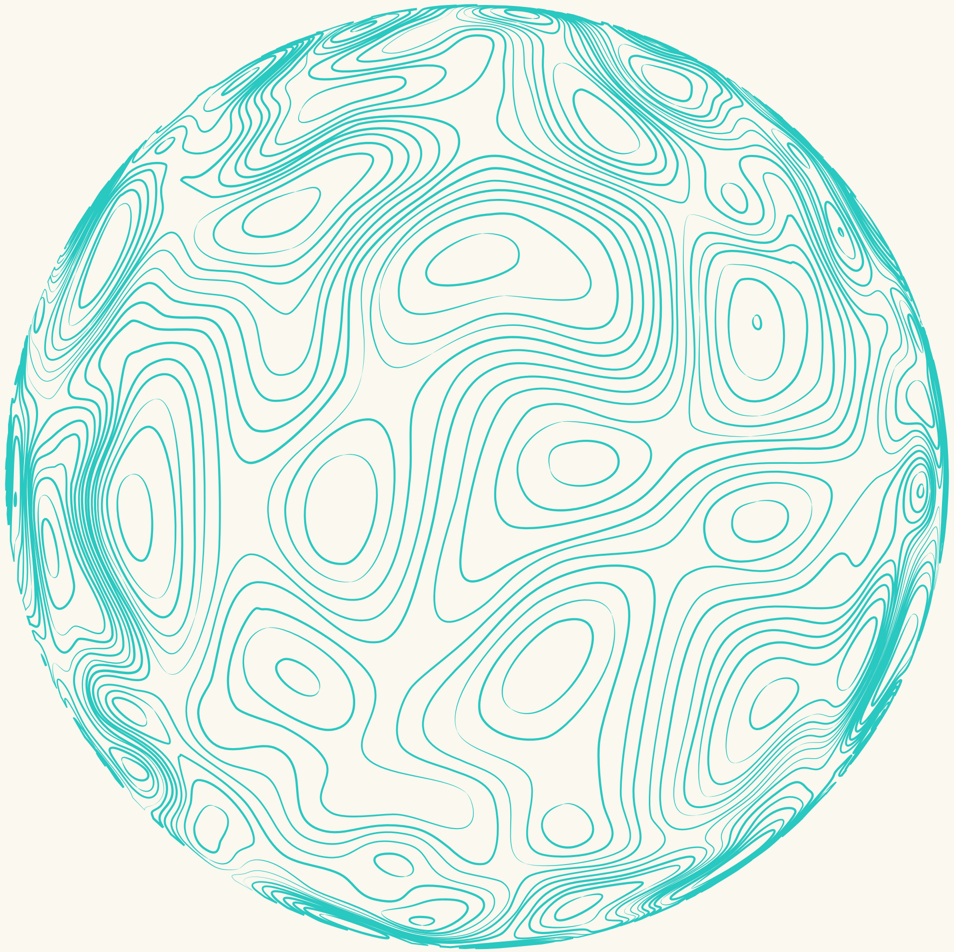
Modelling Summary

For details on the methodology, basis and reference estimates that underpin this modelling summary please refer to the subsequent chapters: chapters 4, 5 and 6.



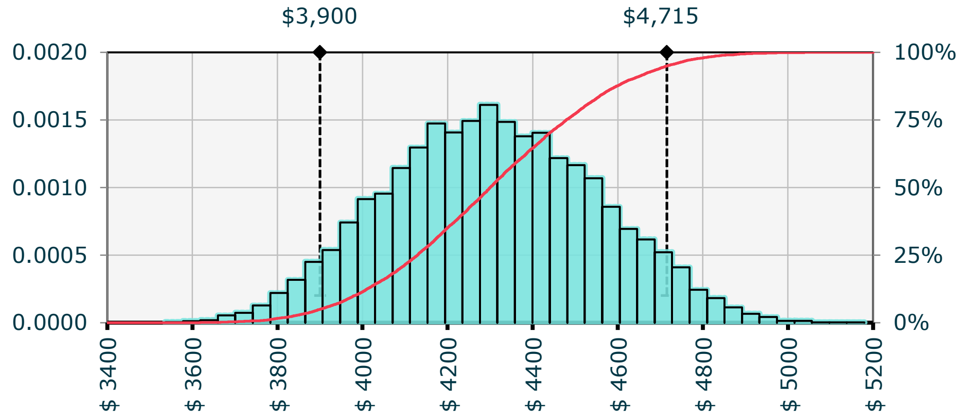
Cost reductions to 2035

Modelling summary

Reference project 1, 100 MWe SOEC based in Victoria, 2035 model results summary

Reference project 1, 2035

- Predicted cost reductions in 2035 for reference project 1 (SOEC, 100 MW) result in a range between 3,900 and 4,715 AUD/kWe.
- The cost reduction is 4,307 AUD/kWe, which is a 41% reduction from the reference estimate.
- Industry maturity leading to a reduction in risk pricing is one of the largest driver of cost reduction and is a common theme with other model results. This SOEC reference facility is also expected to benefit from industrial hub synergies, a result of shared utilities.
- SOEC has greater labour cost compared to AWE and PEM and will benefit more from project management excellence levers.
- Multiple construction levers stack for incremental and considerable savings (lean construction methods, scope minimisation).



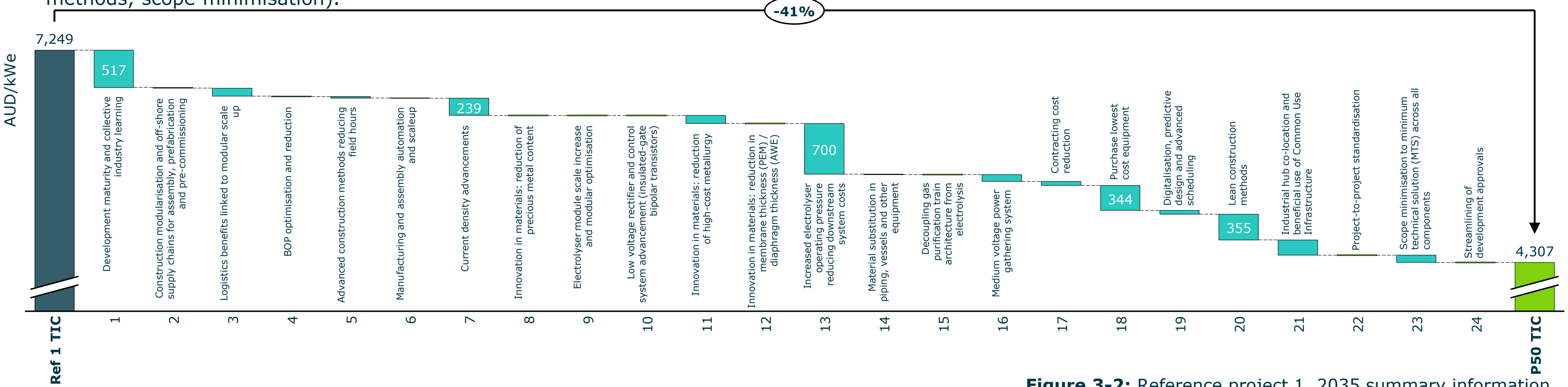


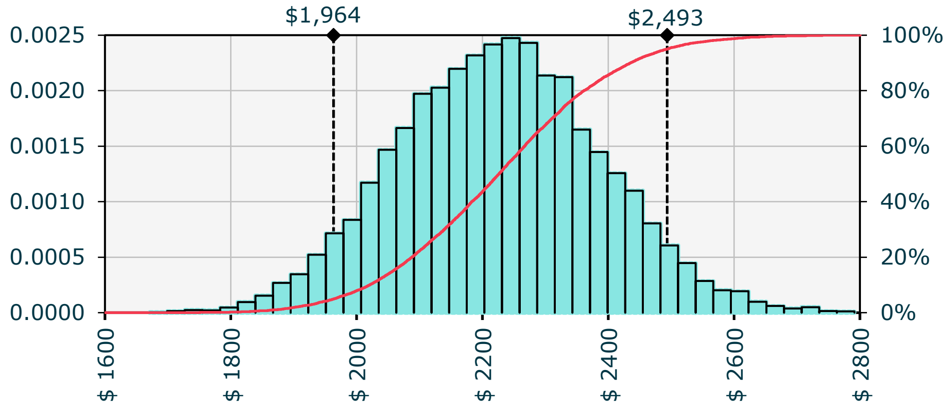
Figure 3-2: Reference project 1, 2035 summary information

Modelling summary

Reference project 2, 1,000 MWe PEM based in South Australia, 2035 model results summary

Reference project 2, 2035

- The scenario indicates capital costs for hydrogen production reduce to $2,290 AUD/kWe which is a 59% reduction from the reference estimate.
- 5% of scenarios have costs as low as $1,960 AUD/kWe, and 95% of scenarios are below $2,490 AUD/kWe.
- Purchasing cheaper equipment yields 23% of TIC savings in the scenario for PEM based projects, reducing TIC by 14%.



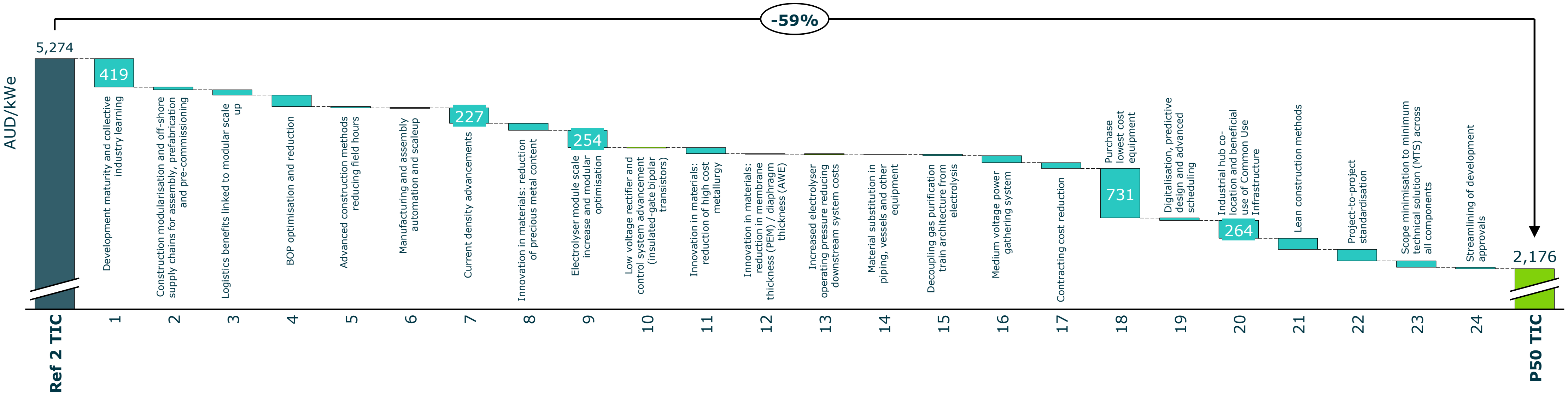


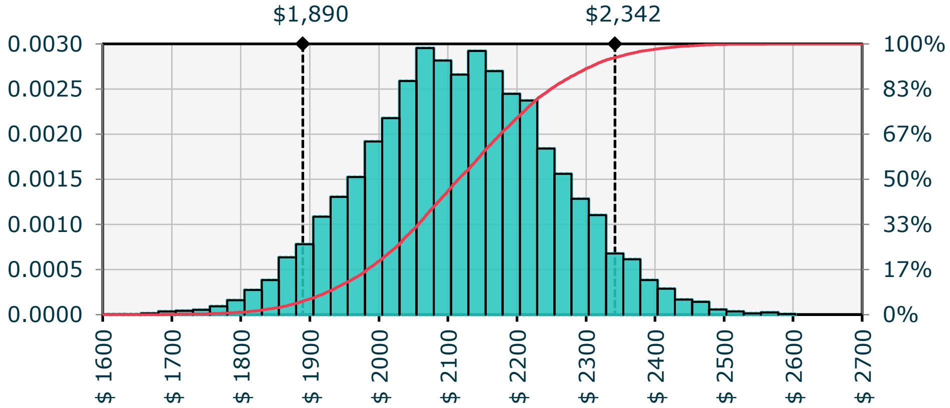
Figure 3-3: Reference project 2, 2035 summary information

Modelling summary

Reference project 3, 1,000 MWe AWE based in South Australia, 2035 model results summary

Reference project 3, 2035

- 90% of scenarios predict 2035 costs for this reference project to fall between $1,890 and $2,340 AUD/kWe.
- Projects in 2035 are expected to cost 57% less than reference project costs in 2025, in the scenario.
- Industry maturity leading to a reduction in risk pricing is the largest driver of cost reduction, and this is a common theme with other model results.
- Purchasing cheaper equipment is predicted to reduce TIC by 11% in the scenario for AWE projects, compared to today's estimates.



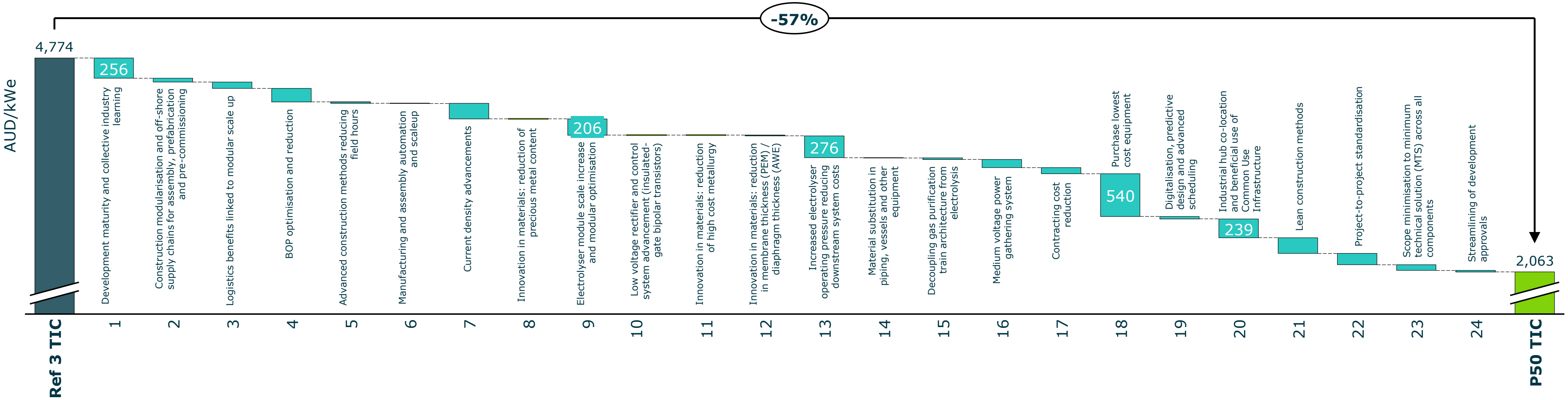


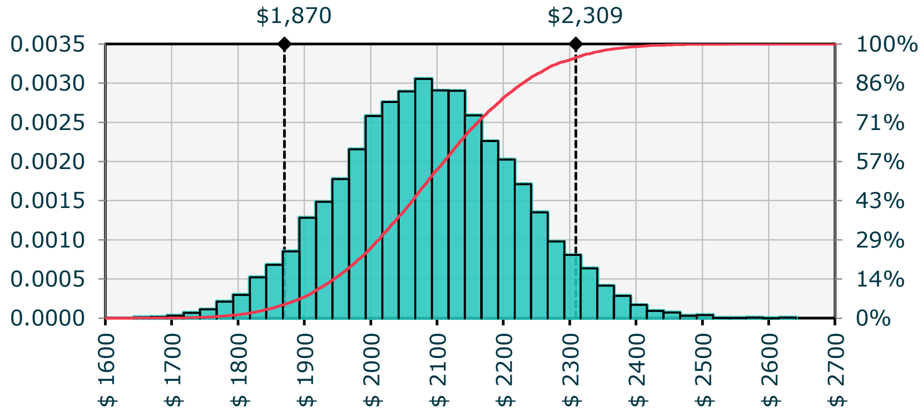
Figure 3-4: Reference project 3, 2035 summary information

Modelling summary

Reference project 4, 10,000 MWe PEM based in Western Australia, 2035 model results summary

Reference project 4, 2035

- Purchasing cheaper equipment is predicted to reduce TIC by 15% in the scenario for PEM mega-scale projects in 2035, compared to today's estimates.
- Total savings in 2035 are 57% in the central scenario which indicates that the benefits of hyper-scaling are not expected to deepen savings, when compared to other reference project results in 2035.



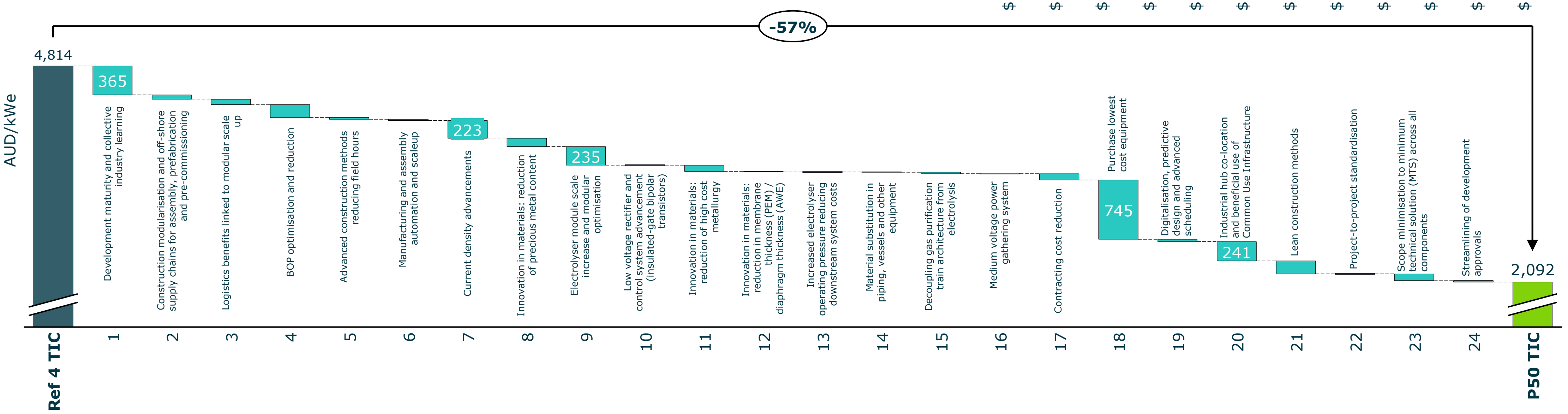


Figure 3-5: Reference project 4, 2035 summary information

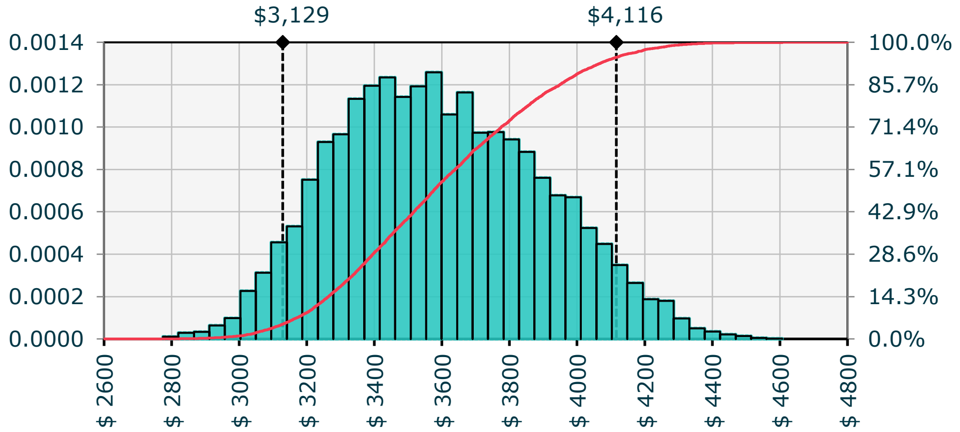
Cost reductions to 2050

Modelling summary

Reference project 1, 100 MWe SOEC based in Victoria, 2050 model results summary

Reference project 1, 2050

- Predicted cost reductions in 2050 for reference project 1 (SOEC, 100 MW) result in a range between 3,129 and 4,116 AUD/kWe.
- The mean cost reduction is 3,754 AUD/kWe, which is a 52% reduction from today's reference estimate.
- Most of the cost reduction savings for reference project 1 are achieved by 2035 (41% reduction), with an additional 11% occurring between 2035 and 2050.



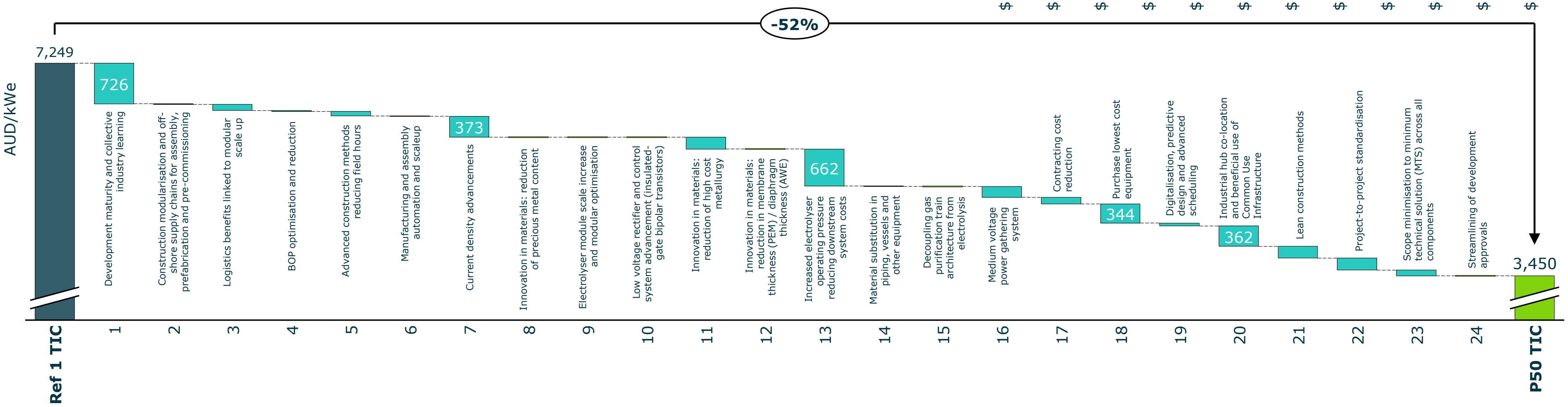


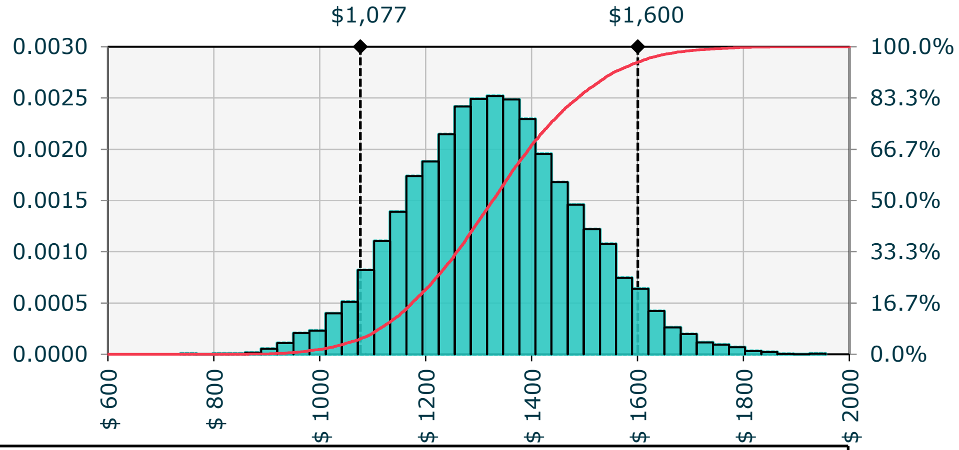
Figure 3-6: Reference project 1, 2050 summary information

Modelling summary

Reference project 2, 1,000 MWe PEM based in South Australia, 2050 model results summary

Reference project 2, 2050

- The scenario indicates capital costs for hydrogen production reduce to $1,283 AUD/kWe which is a 76% reduction from the reference estimate.
- 5% of scenarios have costs as low as $1,077 AUD/kWe, and 95% of scenarios are below $1,600 AUD/kWe.
- Most of the cost reduction savings for reference project 2 are achieved by 2035 (59% reduction), with an additional 17% occurring between 2035 and 2050.



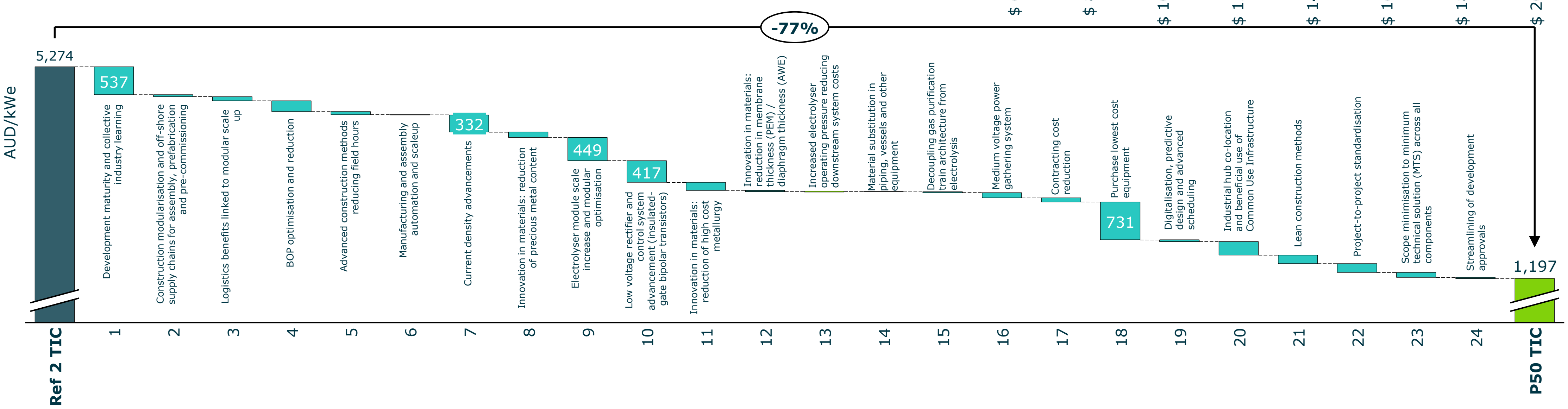


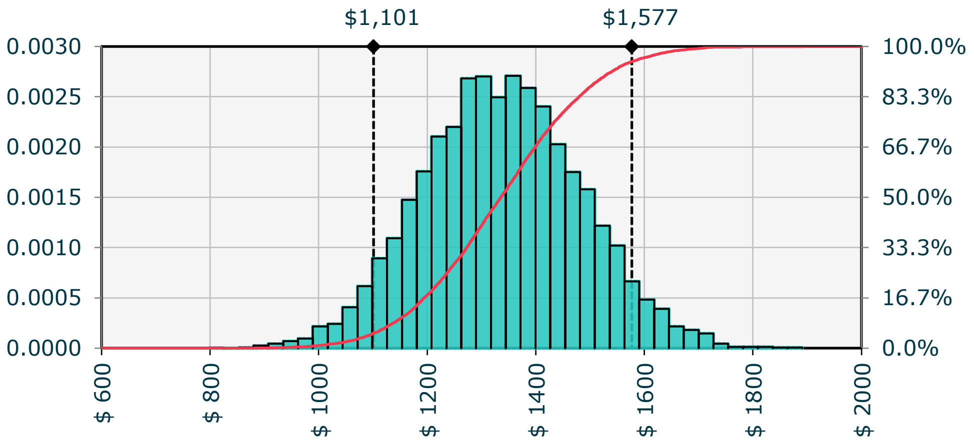
Figure 3-7: Reference project 2, 2050 summary information

Modelling summary

Reference project 3, 1,000 MWe AWE based in South Australia, 2050 model results summary

Reference project 3, 2050

- 90% of scenarios predict 2050 costs for this reference project to fall between $1,101 and $1,577 AUD/kWe.
- Projects in 2050 are expected to cost 73% less than today's reference project estimate.
- Purchasing cheaper equipment is the largest cost reduction item, predicted to reduce TIC by 10% in the scenario for AWE projects compared to today's estimates.
- Most of the cost reduction savings for reference project 3 are achieved by 2035 (57% reduction), with an additional 16% occurring between 2035 and 2050.



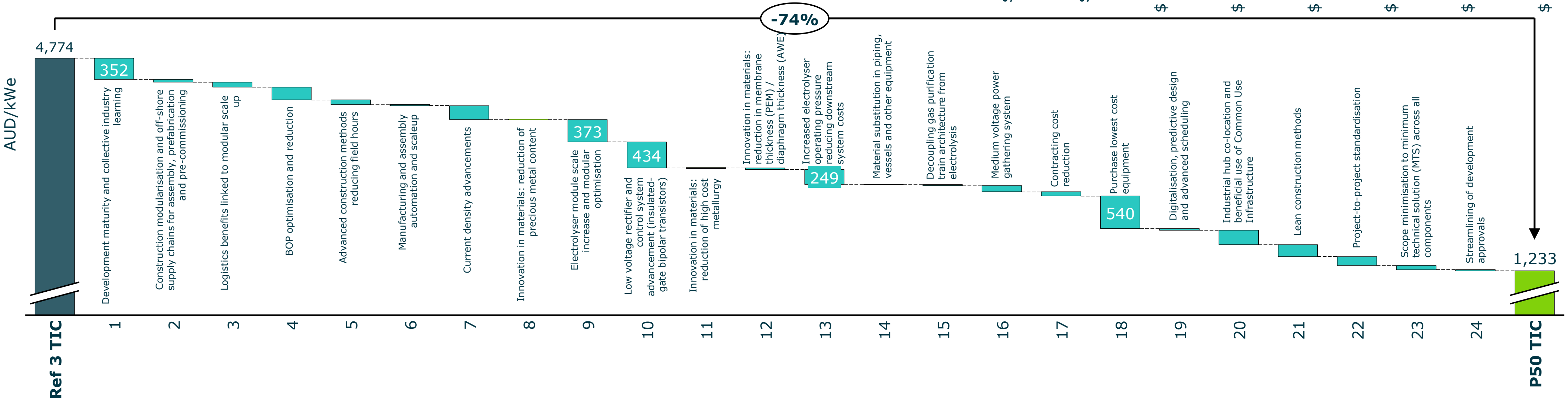


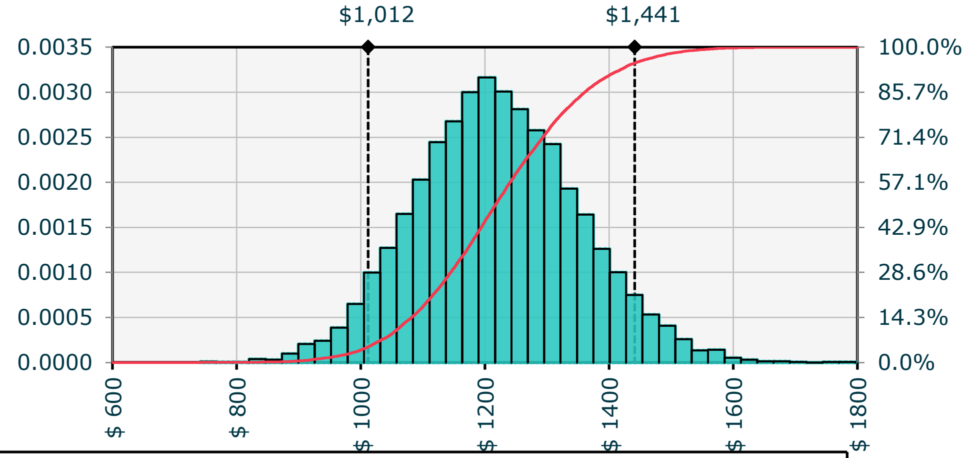
Figure 3-8: Reference project 3, 2050 summary information

Modelling summary

Reference project 4, 10,000 MWe PEM based in Western Australia, 2050 model results summary

Reference project 4, 2050

- Purchasing cheaper equipment is predicted to reduce TIC by 14% in the scenario for PEM mega-scale projects in 2050, compared to today's estimates.
- Total savings in 2050 are 75% in the central scenario which indicates that the benefits of hyper-scaling are not expected to deepen savings, when compared to other reference project results in 2035.
- Most of the cost reduction savings for reference project 4 are achieved by 2035 (57% reduction), with an additional 18% occurring between 2035 and 2050.



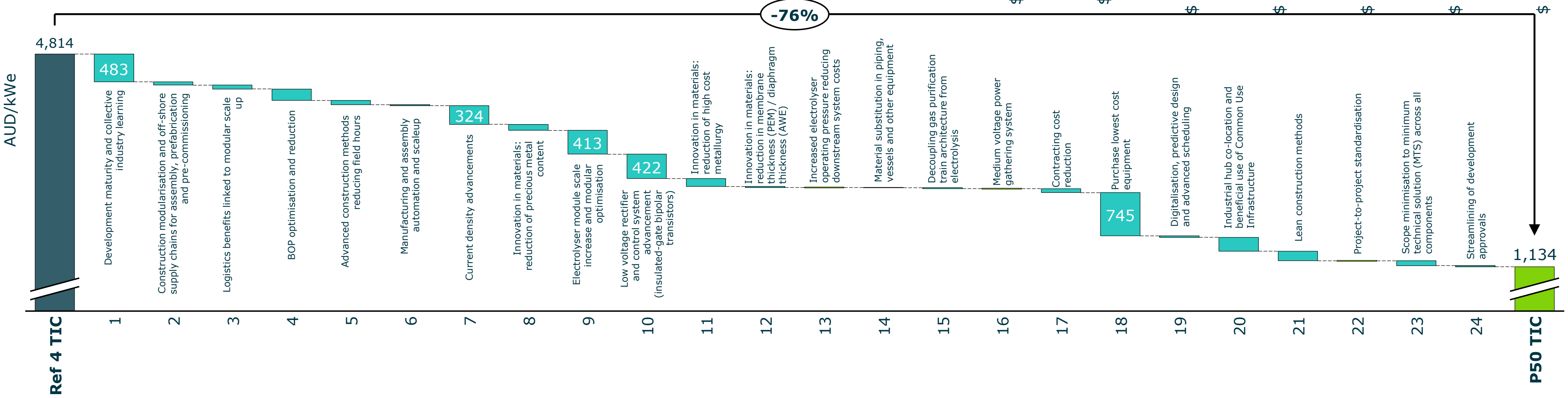
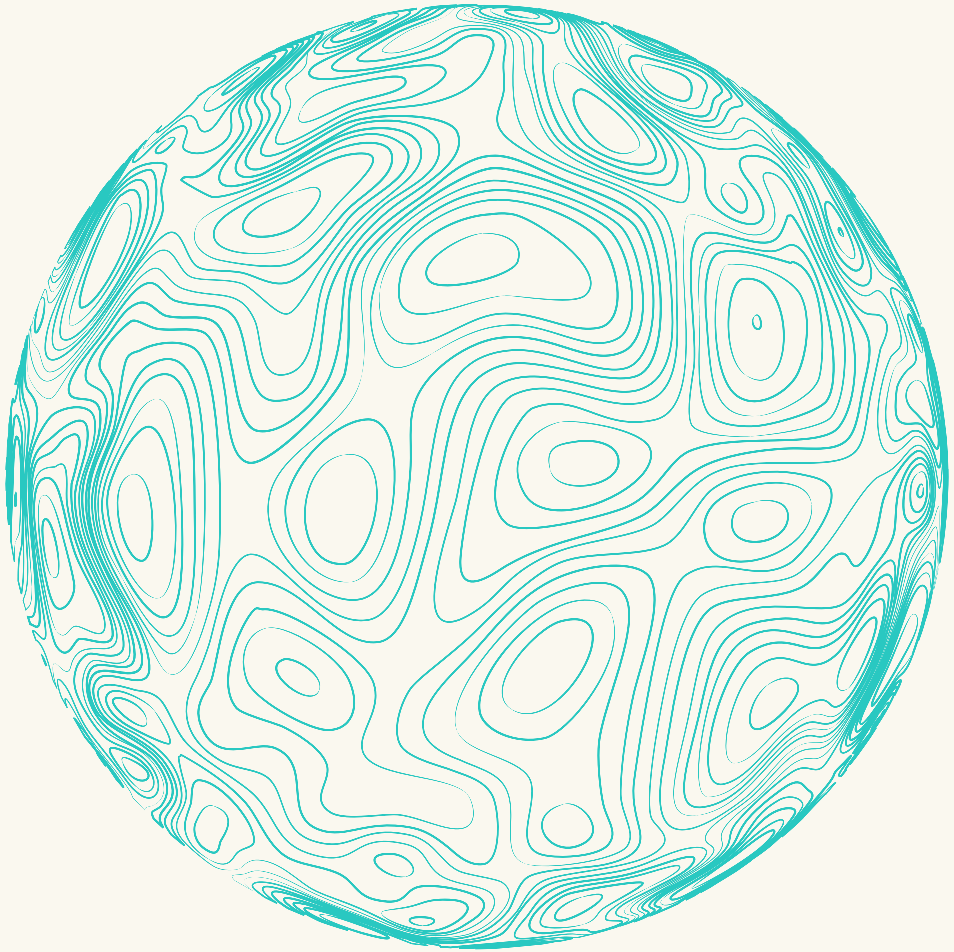


Figure 3-9: Reference project 4, 2050 summary information

4.0

Methodology and Approach



Methodology

This study identified cost-reductions and syndicated these with industry stakeholders

4.1 Methodology

The study established an evidence-based view of hydrogen capital cost reduction pathways through a series of steps:

- Defined the study basis and boundaries (refer to Chapters 1 and 5).
- Defined four reference projects, and developed project TIC estimates for these aligned to Class 5 methodology (in Chapter 6).
- Defined three storage archetypes applicable to reference project 2, and developed project TIC estimates for these aligned to Class 5 methodology (in Chapter 8).
- Identified capital Cost-out Levers using project experience and industry intelligence. These levers were qualitatively ranked, then quantitatively defined covering cost-out potential, applicability, risks and timelines (details in Chapter 7).
- Validated assumptions and lever feasibility through targeted engagement with OEMs, developers, supply-chain participants and ARENA.
- Integrated validated levers into a probabilistic model capturing uncertainty, interdependencies and adoption likelihoods to 2035 and 2050. Details of this are on the following pages. Additional details on the methodology and summary results of the process are in Chapter 3.

The outcomes are capital cost-out projections and sensitivity insights for each reference project.

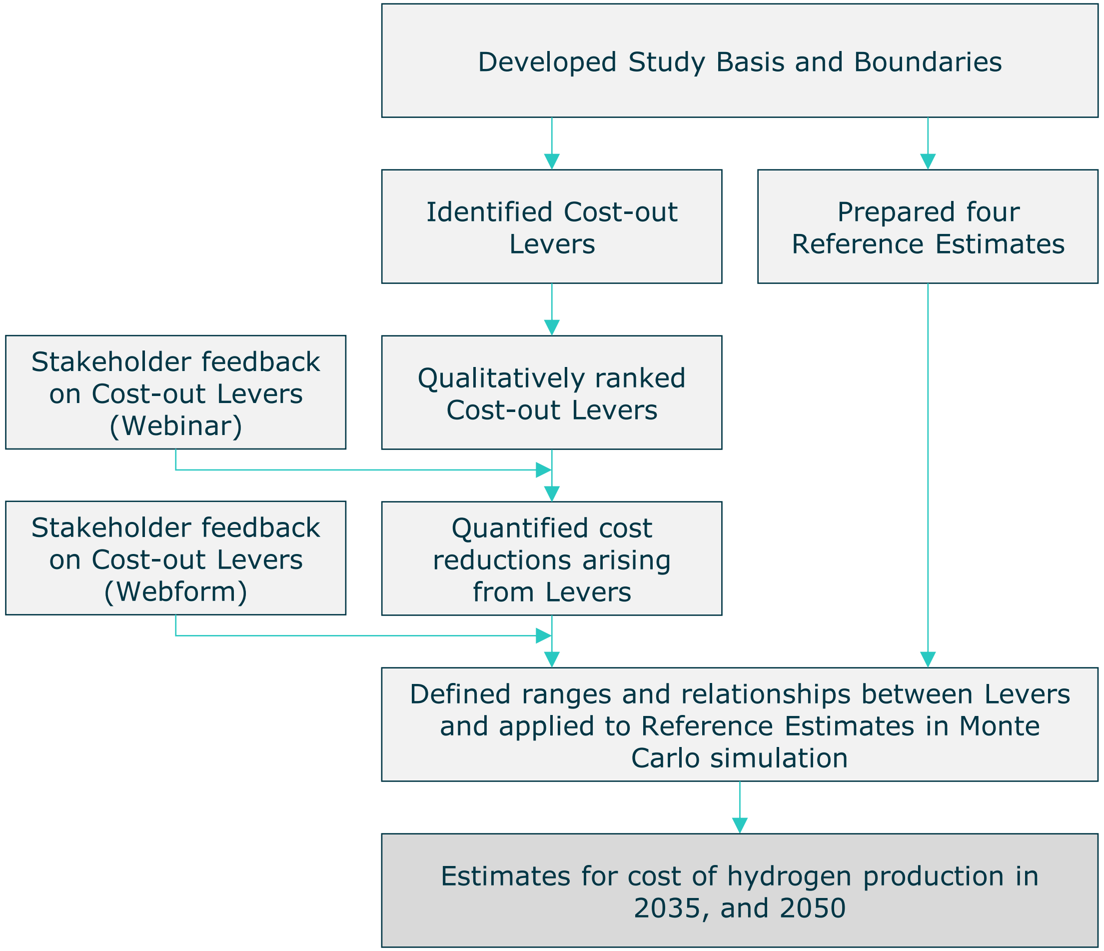


Figure 4-1: Diagram of study methodology

Methodology

The Monte Carlo modelling took deterministic estimates and incorporated uncertainty

The Monte Carlo modelling for this study was conducted in three discrete steps. These are diagrammatically shown in Figure 4-2 below.

1 24 independent, deterministic Cost-out Levers

Each of the 24 levers was defined by low savings, central and high savings cases, for both 2035 and 2050, across 4 reference facilities.

The outcome is a series of savings relative to the reference project TIC. An example of this information set is below:

Lever example	Ref 1	Ref 2	Ref 3	Ref 4
Low Savings (2035)	3.4%	4.6%	2.9%	4.7%
Central Case (2035)	6.3%	8.0%	5.1%	7.7%
High Savings (2035)	15.5%	18.6%	13.3%	17.5%
Low Savings (2035)	5.9%	7.7%	4.9%	7.3%
Central Case (2050)	10.3%	12.5%	8.2%	12.1%
High Savings (2050)	20.0%	23.9%	18.2%	22.8%

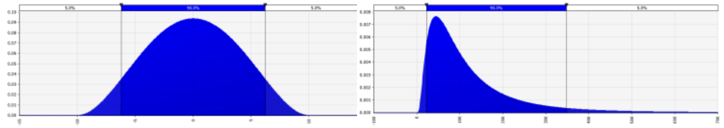
Figure 4-2: Diagram of modelling process

2 Correlations, ranges and probabilities assigned to deterministic outcomes

Each of the cost-out levers had a distribution assigned to the range of savings. The assignment was based on the calculation methodology (from Chapter 7) and uncertainty inherent in forecasting. The uncertainties commonly reflect:

- A range of possible progress by 2035, or 2050
- The range of starting positions in 2026

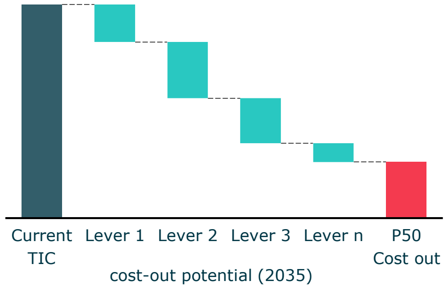
In addition to the assignment of distributions, some cost-out levers are correlated to each other. Details of the correlations are provided on the next page.

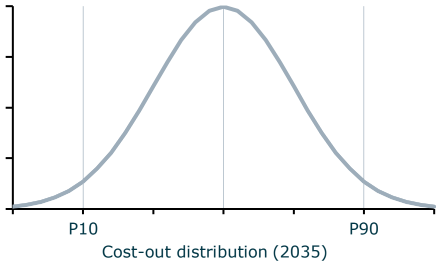


***Example* Distribution**	PertAlt
Low Savings	P90
Central Case	
High Savings	P5

3 Probabilistic analysis and cost-out potential consolidation

Outcomes are produced and presented in this chapter on the following pages.





Methodology

Monte Carlo items can be correlated together, or indicate mutual exclusion

The Monte Carlo environment has regard for relationships between items. Items can be positively, or negatively related. This study:

- Has applied moderate positive correlation (+0.5) where items are related and an outcome in one lever will be linked to cost reduction by other levers
- Has applied moderate negative correlation (-0.5 to -0.7) where items have elements of exclusivity: a result in one item should not overlap with the other.

Details of all levers with active correlations are in Table 7-1 below:

Table 3-1: Correlated items and correlation factors

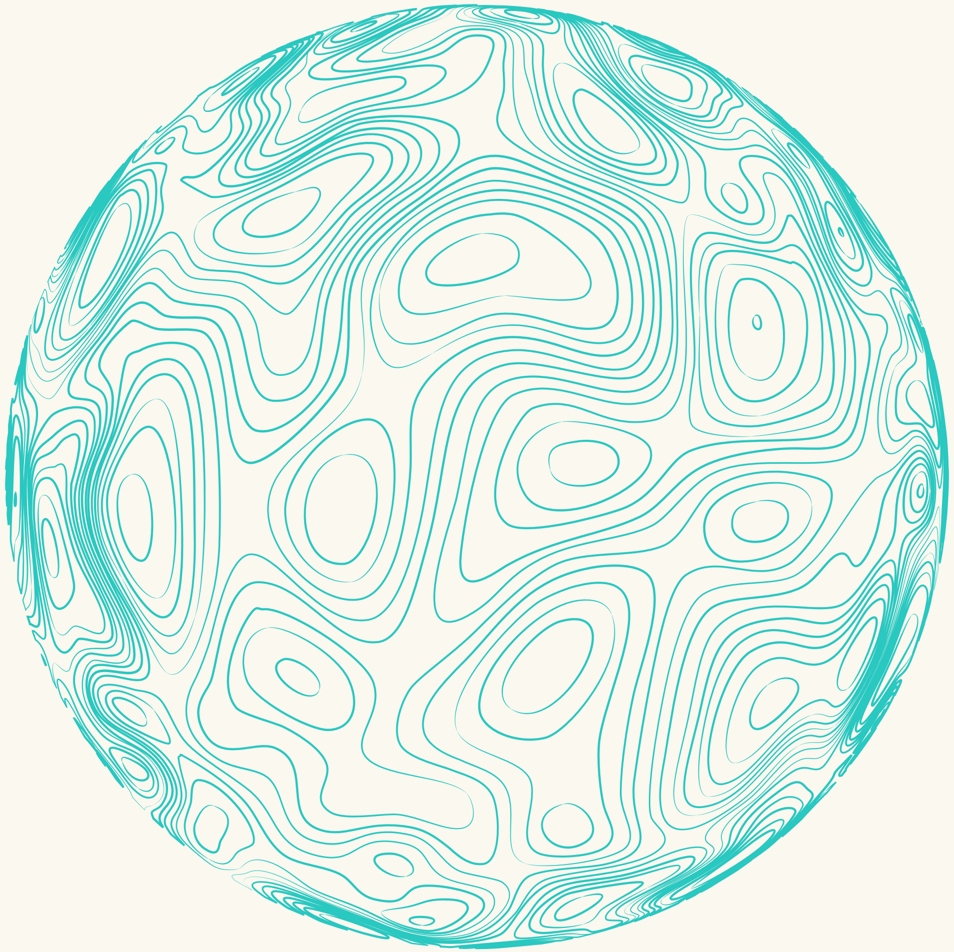
	Correlation factors between cost-out levers[1]	1	2	3	5	9	18	21	22	23	24
1	Development maturity and collective industry learning					-0.5	-0.7				
2	Construction modularisation and off-shore supply chains for assembly, prefabrication and pre-commissioning			0.5					0.5	0.5	0.5
3	Logistics benefits linked to modular scale up		0.5								
5	Advanced construction methods reducing field hours							-0.5			
9	Electrolyser module scale increase and modular optimisation	-0.5									
18	Purchase lowest cost equipment	-0.7									
21	Lean construction methods				-0.5						
22	Project-to-project standardisation		0.5								
23	Scope minimisation to minimum technical solution across all components		0.5								
24	Streamlining of development approvals		0.5								

Notes:

1. Only cost-out levers with active correlations are shown. Levers that do not appear in this matrix have no correlation applied to other items in the modelling environment.

5.0

Basis



Basis

The study basis presents summary estimates in 2025, and predictions of cost reduction

5.1 Basis

This chapter presents the study basis, a definition of the reference projects adopted, and a definition of the estimate methodology. All estimates are in real 2025 AUD. Cost reductions stated in 2035 and 2050 are based on purchases placed in that year.

Large equipment items are traded in foreign currencies, primarily the U.S. dollar and the Euro. Exchange rates are considered constant for the study and are in Table 5-1 below.

Table 5-1: Foreign exchange rates

Currency	Exchange factor to 1 AUD
US Dollars	0.65
Euro	0.56

The estimates are based on equipment and material quantities derived from the concept definition of the reference projects. From there, historical rates or direct budgetary quotes from Worley's cost database are applied to derive the costs for material supply and installation. This includes data for indirects from similar projects. Location-specific installation rates are applied to direct costs based on historical rates for similar projects in each location.

These direct costs are built on a bottom-up basis from defined costs containing Procurement, Fabrication & Transport, site construction and commissioning. Site Works estimates are applied throughout the categories outlined in Table 5-2.

Table 5-2: Cost estimate categories

Direct Costs	Contains
Power Systems	HV Switchyard, Transformers, Reticulation and power stability systems, BESS to maintain power system stability and does not support production
Electrolysis	Stacks, LV rectifiers, gas purification, coolers, heaters, dryers. Typical scope of OEM supply.
Electrolyser Stacks	*Subcomponent of Electrolysis: Stacks*
Electrical Equipment	*Subcomponent of Electrolysis: LV transformers, rectifiers, controls etc.*
Purification and treatment	*Subcomponent of Electrolysis: gas purification, coolers, heaters, dryers etc.*
Compression	H_2 compression to 30 barg downstream of electrolysis units
Steam Generation	WHRU, ducting and steam system, boiler feedwater system
Utilities	Water Demineralisation, Cooling System, Plant Air, Nitrogen, Fire water etc.
Non-process infrastructure and connections	Buildings (Control room, stores, warehousing, communications infrastructure), Site Prep & Civils, Service Connections
Indirect Costs	
Common Indirects	Includes temporary facilities, site services
Engineering and PM	Engineering, Project management (PM)
Owners' costs	Owners' costs, legal fees, Owner's PM, permitting etc.

Basis

5.2 Reference project definition

Four reference projects are defined which span a range of scale and configurations

As a basis for the assessment, this study presents a set of four reference projects. These reference projects are created to cover the relevant span of technology, scale and location today and out to 2050.

The reference projects:

- Span a range between 100 and 10,000 MWe
- Comprise a range of electrolysis technologies, SOEC, PEM, and AWE
- Include equipment for grid stability support for projects representing behind the meter developments, and
- Apply location factors for a range of locations in Australia that are known to be developing hydrogen production facilities.

The reference projects are summarised to the right in Table 5-3. Additional details and assumptions are presented on the following page.

Table 5-3: Reference project descriptions

Parameter	RP1	RP2	RP3	RP4
Description	Modest scale grid-connected SOEC	Mid scale dynamic PEM	Mid scale dynamic AWE	Large scale dynamic PEM
Electrolyser size (MWe)	100	1,000	1,000	10,000
Electrolyser technology	SOEC	PEM	AWE	PEM
Location	VIC	SA	SA	WA
Power Source	Transmission grid connected	Behind the meter[1]	Behind the meter[1]	Behind the meter[1]

Notes:

1. Costs for electricity generation and electricity storage to support production are not included in reference project estimates. Cost estimates for these reference projects include the equipment required for some grid stability support.

Basis

Reference project metrics

Metrics for the reference projects are a function of the technology and the power supply

The plant metrics and capacities for the reference projects are in Table 5-4.

Reference project assumptions

The reference projects are underpinned by a series of assumptions:

- Grid connected reference projects are assumed to be entirely grid firmed and do not require electrical storage or equipment for grid stability support.
- For behind the meter reference projects (RP2-4) the following assumptions are applied:
  - The supply of electricity is from variable renewable sources (solar and wind resources).
  - The hydrogen production facility production varies with renewable power generation.
  - BESS capacity considers 12 hours essential power (utilities and standby power) for electrical storage, this storage is not for hydrogen production.
- Reference project 1 which uses SOEC considers steam supplied from a WHRU installed on an existing industrial site adjacent to the HPF. Costs for WHRU are included.
- Dry air cooling is adopted at all locations. The exception is an evaporative cooling tower for SOEC cooling, which requires a 10 MW cooler.
  - Electrolyser cooling for AWE and PEM is achieved by closed loop air cooling, where heat is removed by circulating cooling water. The hot cooling water is cooled by ambient air.

Table 5-4: Reference project metrics and capacities

Parameter	Units	RP1	RP2	RP3	RP4
Electrolyser technology	-	SOEC	PEM	AWE	PEM
Energy demand[1]	kWh / kg H_2	39.6	55.1	55.1	55.1
Efficiency[2]	%	19%	65%	65%	65%
Electrolyser size	MW	100	1,000	1,000	10,000
Hydrogen production (peak)	tpd	60	440	440	4,400
BESS Size	MW / MWh	-	40 / 480	40 / 480	400 / 4,800
Electrolyser outlet pressure	barg	1.0	30	0.2	30
WHRU thermal duty	MW	20	-	-	-
Feeders	-	1 x 132 kV	2 x 275 kV	2 x 275 kV	5 x 500 kV

1. Hydrogen production and purification only (refer to Figure 1-1), figures are start-of-life. SOEC energy demand presented on a steam-fed (not water-fed) basis.
2. Efficiency based on lower heating value (LHV) of hydrogen (120 MJ/kg H_2).

Basis

This study adopts a representative architecture of electrolyser modules comprising sub-units.

Electrolysis configuration

The electrolysers in the reference projects are configured in adjacent trains containing multiple modules. Refer to the illustrative diagram adjacent, Figure 5-2. For this study, the following concepts are defined:

- Electrolyser stacks are comprised of multiple electrolytic cells, indicated in Figure 5-1.
- Each module includes the electrical equipment, electrolyser stacks and balance of stack equipment (electrolyte circulation, gas separation, etc.). The number of electrolyser stacks in a module depends on the technology, licensor and physical size of the module. Reference project cost estimates are based on a modular scale of 20 MWe. This is representative of the range of configurations offered by multiple OEMs today.
- Each module is associated with subsequent balance of plant equipment (e.g. hydrogen purification) and cooling water circuit.
- Compression, water trea[…]aining utilities are shared between modules.

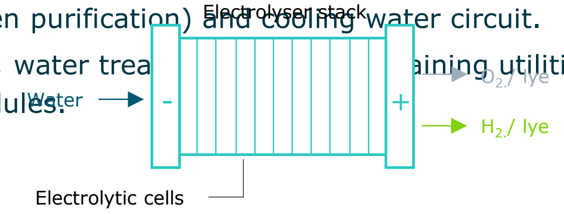


Figure 5-1: Electrolyser stack comprising electrolytic cells (AWE)

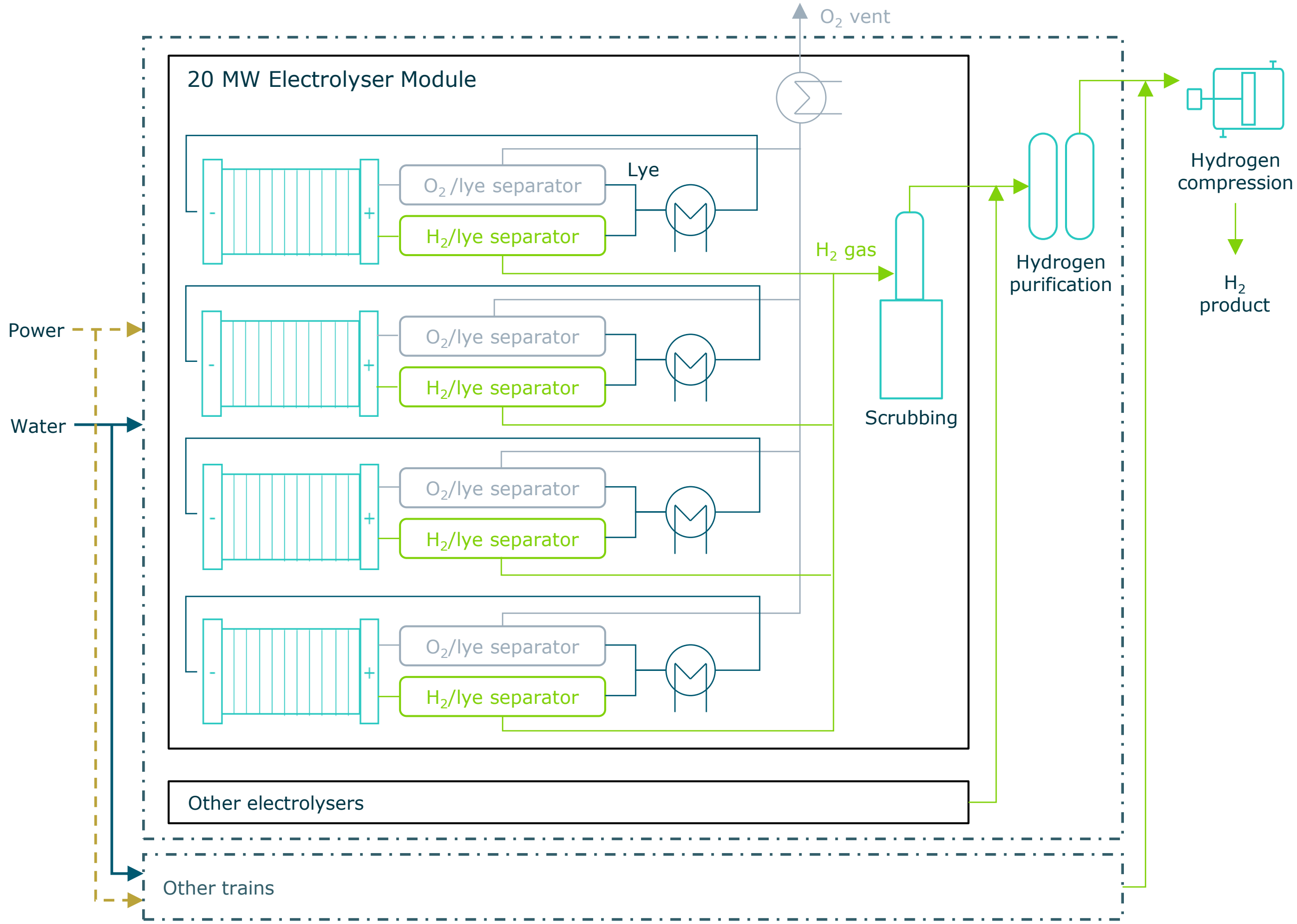


Figure 5-2: Generic Electrolyser schematic (AWE, illustrative only)

Basis

Electrical system architecture is linked to electrolyser module size

Electrical configuration

The size and configuration of the electrolysers and the electrical equipment are configured in tandem. This study adopts 20 MWe electrolysers, which pair directly to power system infrastructure.

Figure 5-3 to the right shows the power system architecture adopted for the four reference projects. The architecture depends on the quantum of power and the carrier voltage arriving.

In general:

- The power systems are linked to the scale of the electrolyser modules (refer to Figure 5-2 on the previous page).
- Electrolyser modules are grouped into trains, and each train has a dedicated HV transformer.
- Each 20 MW electrolyser module will have its own medium voltage (MV) transformer and rectifier.
- The incoming power HV switchyard is common to the site, and the incoming voltage is related to the scale of the reference project.
- The costing basis is for nil redundancy is provided in the number of transformers.

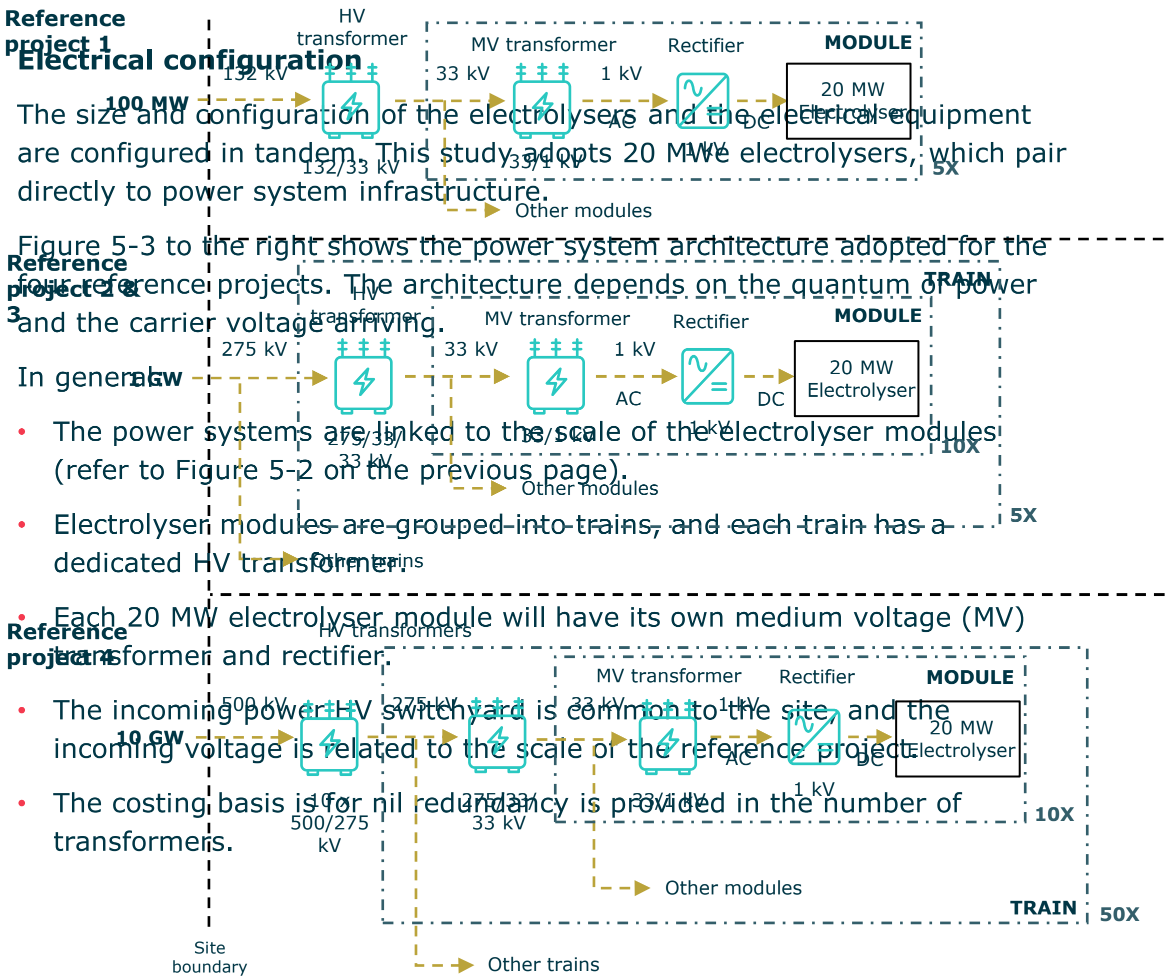


Figure 5-3: Electrical configuration schematic for the four reference projects.

Basis

Reference project estimates in this report align to Class 5 methodology

5.3 Estimate classification

The capital cost estimates for project definition and estimating methodology are aligned to AACEI Class 5 classification. Table 5-5 displays the AACEI class classification matrix, outlining the estimating methodologies for Cost classified 1 through 5. Classifications with higher number (lower definition) are utilised when less of the project is defined which results in greater variations in costing accuracy and are not as far along in the project commercialisation lifecycle.

Class 5 estimates are prepared for strategic business planning purposes, such as, but not limited to, market studies, assessment of initial viability, evaluation of alternative scheme, project screening, project location studies, evaluation of resource needs and budgeting, long-range capital planning.

Aligned with the estimate methodology, the reference project estimates apply contingency and an allowance for design growth which reflects the estimate classification of plant definition, and nascent industry maturity:

- **Contingency** of between 25 and 30% is applied to all direct and indirect costs,
- **Design growth** allowance of between 10 and 15% is applied to direct costs

Table 5-5: Class cost estimate classification

Estimate Class	Project Definition (% of Complete Definition)	Intent of Estimate	Methodology	Expected Accuracy Variation in Low and High Ranges
Class 5	0-2%	Concept Screening	Capacity factored, parametric models, judgement, or analogy	**Low:** -20% to -50% **High:** +30% to +100%
Class 4	1-15%	Study or feasibility	Equipment factored or parametric models	**Low:** -15% to -30% **High:** +20% to +50%
Class 3	10-40%	Budget authorisation or control	Semi-detailed unit costs with assembly level line items	**Low:** -10% to -20% **High:** +10% to +30%
Class 2	30-70%	Control or bid / tender	Detailed unit cost with forced detailed take-off	**Low:** -5% to -15% **High:** +5% to +20%
Class 1	50-100%	Check estimate or bid / tender	Detailed unit cost with detailed take-off	**Low:** -3% to -10% **High:** +3% to +15%

Basis

Global electrolyser deployment is forecast to reach 110 GW by 2030

5.4 Deployment rates

The range of forecast global deployment of electrolysers by 2030 is broad. Delays and cancellations in recent years have significantly impacted electrolyser project completion. The International Energy Agency (IEA) publish and maintain a database of hydrogen production facilities in operation, and through various stages of project readiness.

The largest volume is categorised as ‘Announced capacity’ records a volume of announced global electrolyser capacity of 440 GW globally by 2030. Announced capacity is not a good proxy for development expectations as it includes all projects, including a fraction with low-likelihood of reaching operation. The same IEA database assigns a ‘moderate to strong’ likelihood to a subset of this volume: 110 GW of projects.

The moderate-strong IEA projection aligns closely with a similar BloombergNEF (BNEF) forecast (BNEF, 2024). Details are in the adjacent figure.

A considered average has therefore been taken in forecasting the global electrolyser deployment rate, incorporating the BNEF values and the project’s IEA categorise as proceeding with a moderate-to-strong likelihood. This considered average is shown in Figure 5-4, scaling up to ~110 GW by 2030.

Worley rely on these credible forecast deployment rates as baseline for future assessments of cost reduction. The predictions of future cost reduction rely on continued deployment and learning at the increasing pace indicated in Figure 5-4.

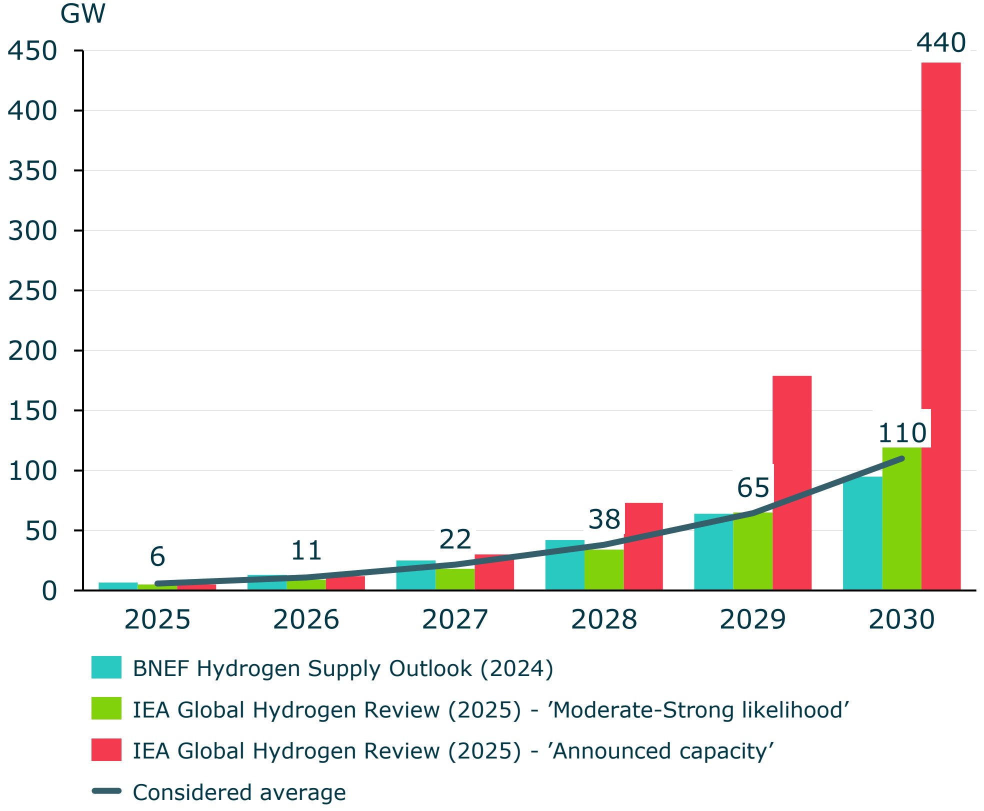
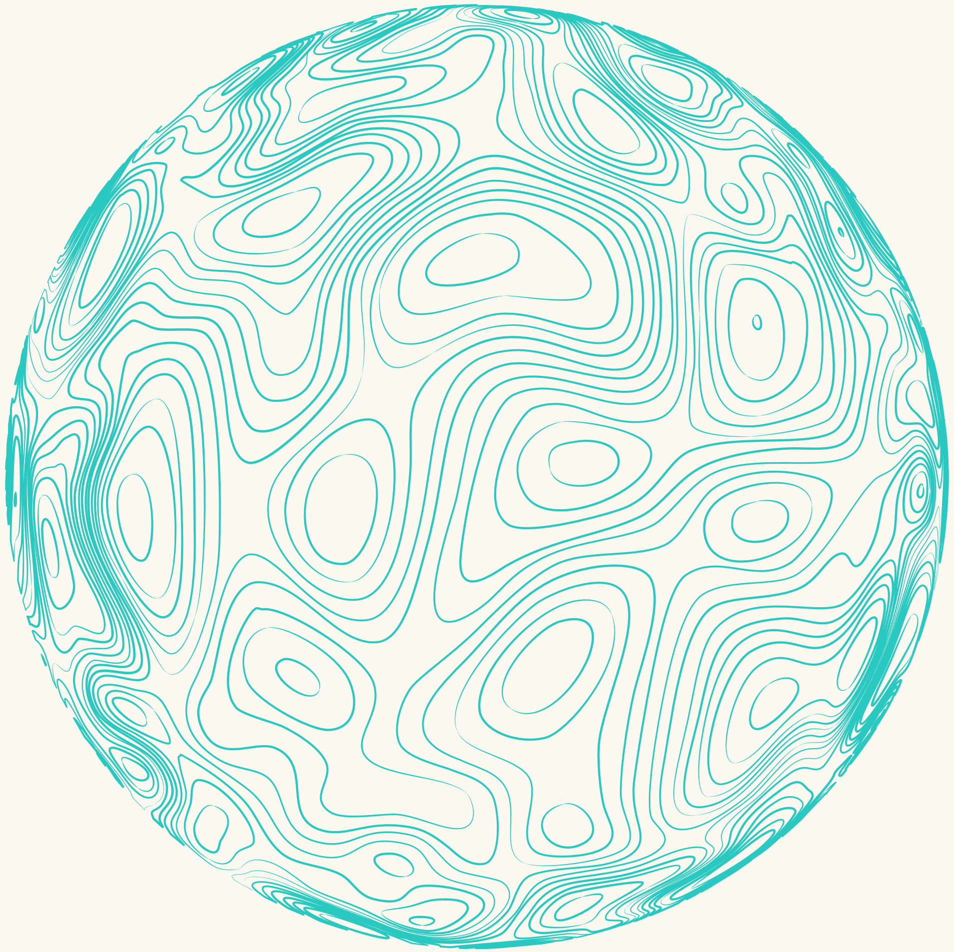


Figure 5-4: Electrolyser global deployment capacity forecast (2025-2030)

6.0

Reference Project Estimates



Reference Project Estimates

Material cost variations between projects arise from different electrolyser stack estimates

6.1 Reference project estimates

Total installed costs were estimated for the reference projects aligned to the basis outlined in the previous chapter. Outcomes of the estimate are presented in Table 6-1 below.

Table 6-1: Summary of cost estimates

Direct Costs	Ref 1: 100 MW SOEC VIC			Ref 2: 1 GW PEM SA			Ref 3: 1 GW AWE SA			Ref 4: 10 GW PEM WA		
	AUDm	*AUD/kWe*	*%*	*AUDm*	*AUD/kWe*	*%*	*AUDm*	*AUD/kWe*	*%*	*AUDm*	*AUD/kWe*	*%*
Power Systems[1]	19	189	3%	386	386	7%	386	386	8%	4,226	423	9%
Electrolysis	387	3,874	53%	3,210	3,210	61%	2,486	2,486	52%	29,346	2,935	61%
Electrolyser Stacks	*335*	*3,347*	*46%*	*2,897*	*2,897*	*55%*	*2,142*	*2,142*	*45%*	*25,532*	*2,553*	*53%*
Electrical Equipment	*43*	*426*	*6%*	*249*	*249*	*5%*	*273*	*273*	*6%*	*3,228*	*323*	*7%*
Purification and treatment	*10*	*102*	*1%*	*65*	*65*	*1%*	*71*	*71*	*1%*	*586*	*59*	*1%*
Compression	62	623	9%	-	-	-	274	274	6%	-	-	-
Steam Generation	29	293	4%	-	-	-	-	-	-	-	-	-
Utilities	19	187	3%	114	114	2%	118	118	2%	1,000	100	2%
Non-process infrastructure and connections	8	74	1%	87	87	2%	89	89	2%	486	49	1%
Indirect Costs												
Common Indirects	100	1,002	14%	760	760	14%	709	709	15%	6,501	650	14%
Engineering and PM	67	671	9%	477	477	9%	494	494	10%	4,354	435	9%
Owners' costs	34	335	5%	240	240	5%	217	217	5%	2,229	223	5%
Total	**725**	**7,249**	**-**	**5,274**	**5,274**	**-**	**4,774**	**4,774**	**-**	**48,143**	**4,814**	**-**

Notes:

1. Reference project 1 does not include BESS for power system support in the Power Systems subtotal.

Reference Project Estimates

Electrolyser stack costs comprise between 45-55% of the total estimate

6.2 Normalised comparisons

In Figure 6-1 to the right are the reference projects presented on an AUD/kWe basis. These estimates reflect Worley's cost data and norms applied for the methodology adopted.

Electrolyser stacks are the largest cost item in each reference project, contributing between 45% and 55% of the total direct costs. A further 17-26% comprises balance-of-plant costs, and 27-30% for project costs. Electrolyser stacks were also the primary source of cost variability between reference projects

The efficiency-of-scale effect in the 10 GWe reference project is masked by competing factors beyond 1 GWe. The primary factors at play are:

- Electrolyser and power systems decompose into repeatable units of approximately 250 MWe. Today's repeatable structure minimises cost benefits of scale.
- As scale increases there comes a tipping point where higher voltage transmission is required. Reference project 4 introduces additional HV power infrastructure at cost when compared to the other reference projects. Refer to Figure 5-3 which indicates this additional stage of electrical transformation.
- Direct costs in WA are ~12% higher than in SA, driven primarily by the cost of labour.

SOEC is an emerging technology which uses thermal energy to overcome some energy required for the hydrogen production reaction. The cost of steam systems in reference project 1 comprise 4% of total cost.

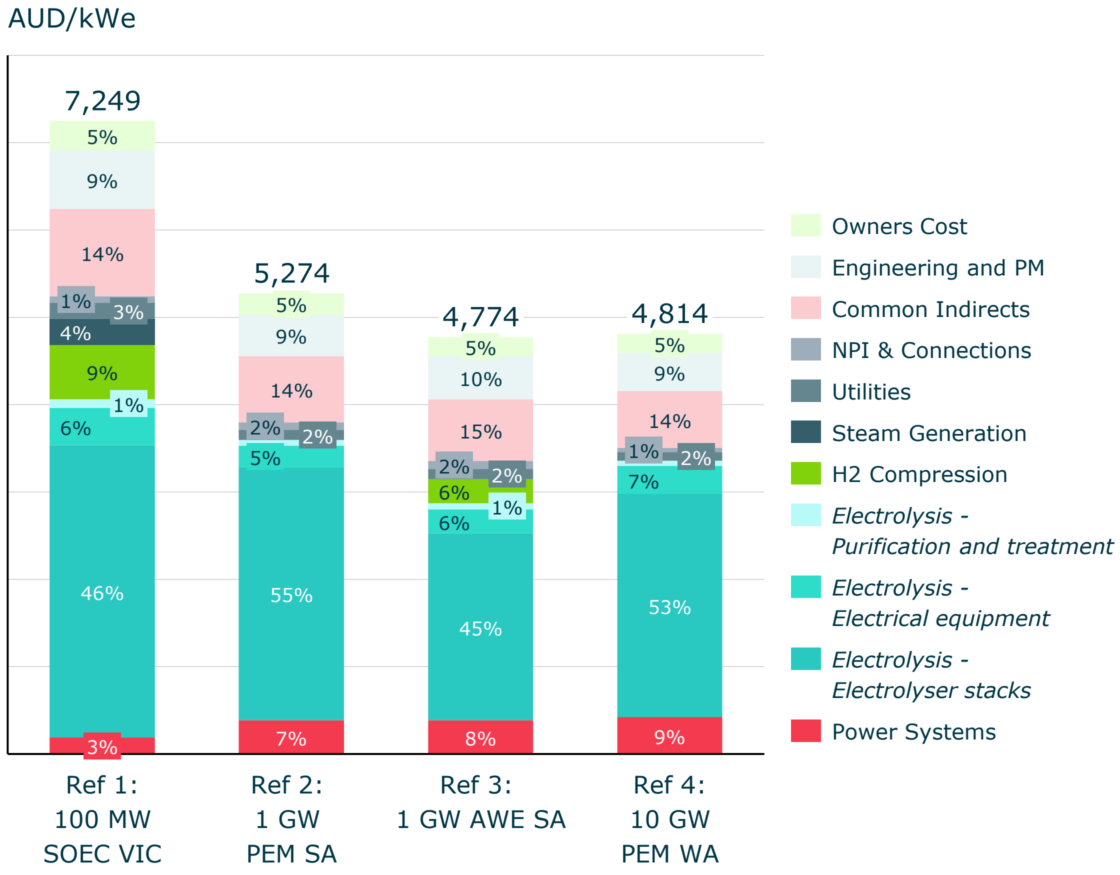


Figure 6-1: Reference project cost breakdowns (AUD/kWe)

Reference Project Estimates

Reference cost estimate inputs are broken down into cost items to assess impact.

6.3 Reference cost inputs

Reference cost estimates are further evaluated by grouping them into their cost types and then breaking them down into their cost items. The cost breakdown methodology is shown below in Figure 6-2. Where necessary, the indirect costs are applied *pro-rata* on direct costs.

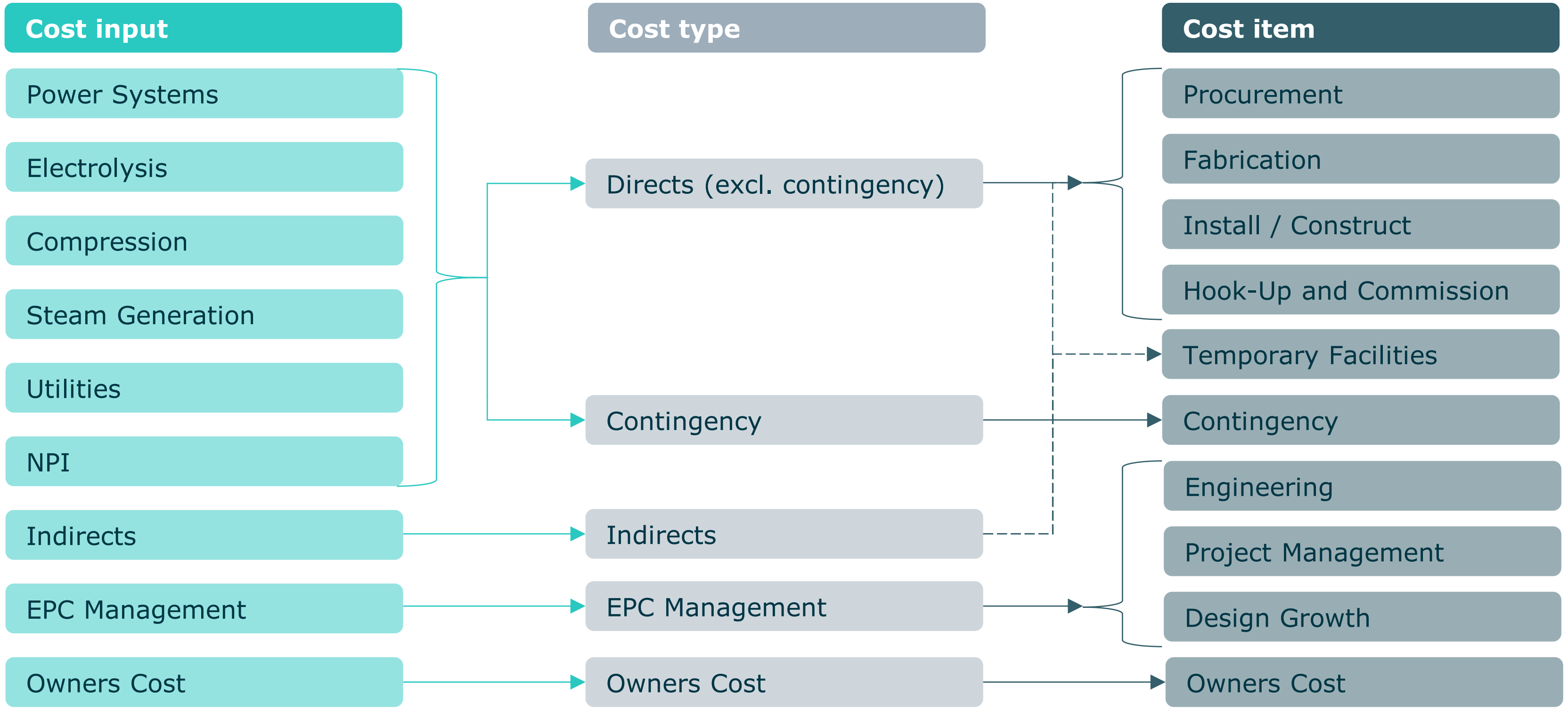


Figure 6-2: Cost breakdown methodology

Reference Project Estimates

When indirect costs are attributed Electrolysis stacks contribute 78% of the reference estimate

Reference cost items are presented below in Figure 6-3 for reference project 2. Contributions greater than 1% of the total estimate are labelled.

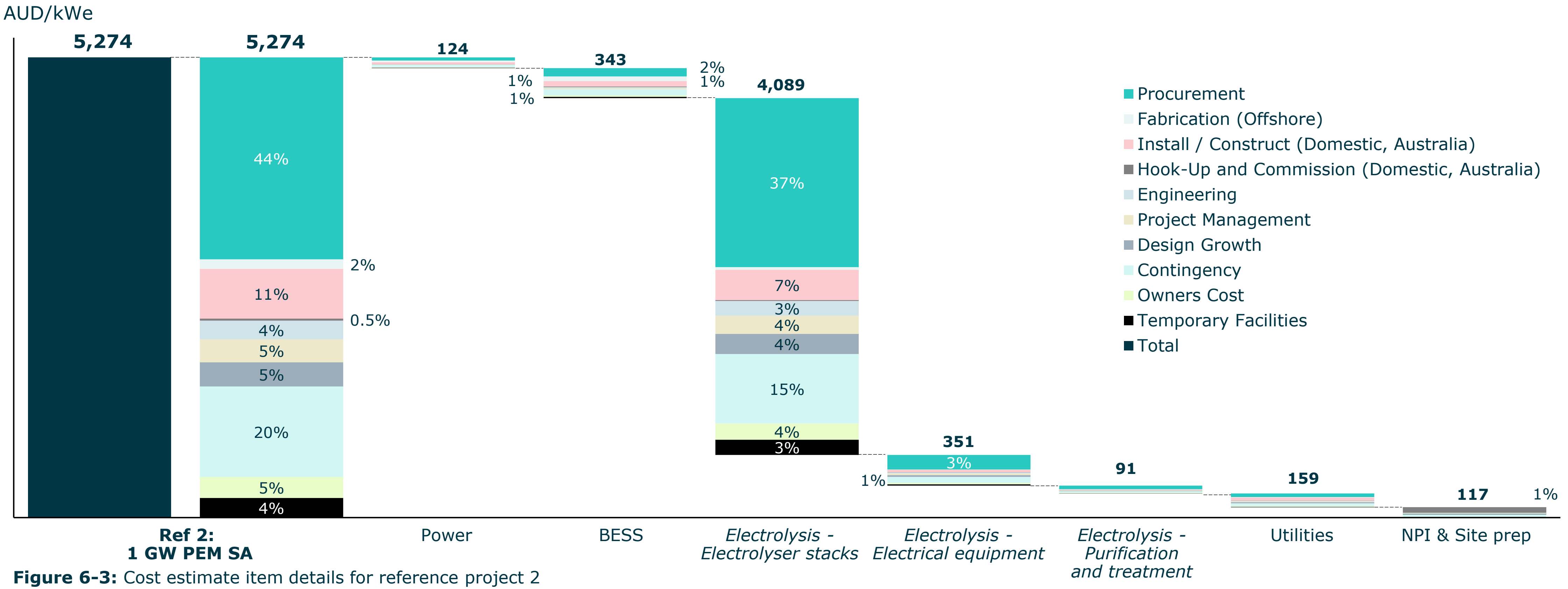
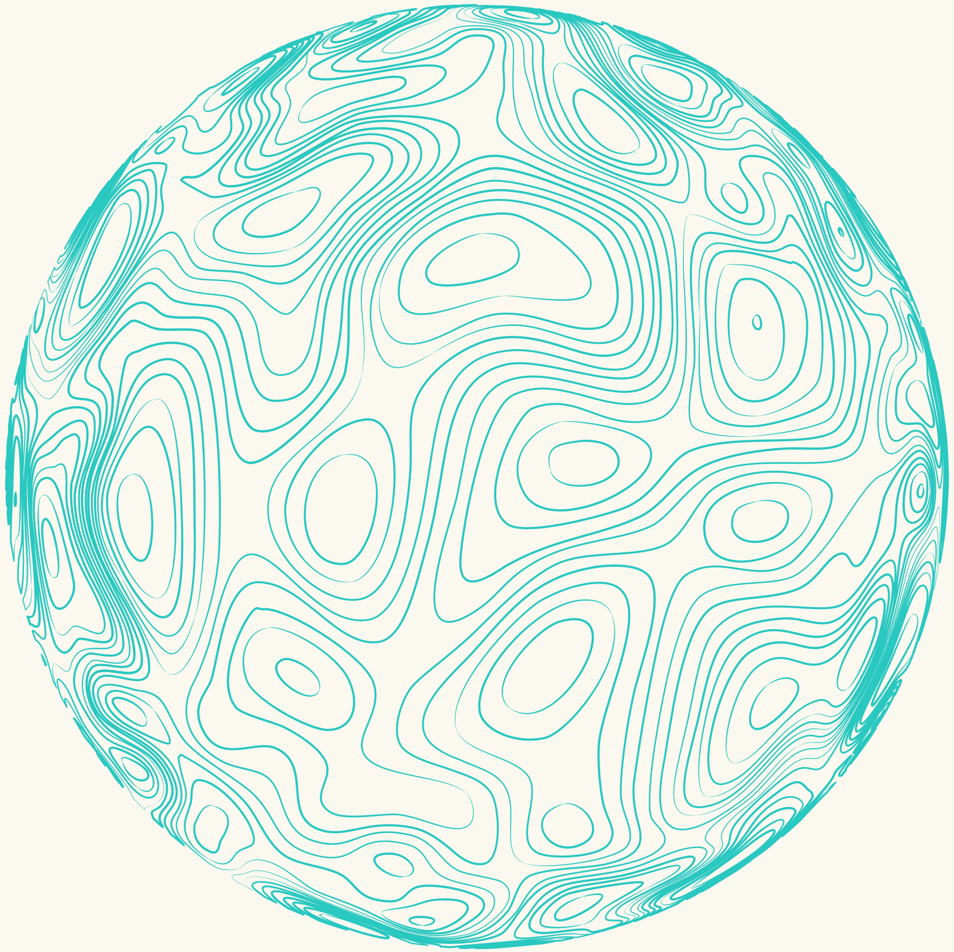


Figure 6-3: Cost estimate item details for reference project 2

7.0

Cost-out Levers



Cost-Out Levers

24 independent cost-out levers are identified, grouped and quantified within this chapter

Table 7-1: Themes and definitions

This chapter summarises the 24 independent Cost-out Levers (levers) identified that are predicted to

Theme	Definition	QTY
Supply Chain Maturity	Cost reduction benefits from sustained demand that supports supply chains reaching maturity and commoditisation thereby reducing cost	**5**
Technology Advancement	Cost reductions dependent on core technology changes or advancements, probable areas of current and future research	**9**
Systems Integration	Cost reductions arising from different system thinking and production configurations	**2**
Commercial Choice	Cost reductions arising from commercial choices developers may take, these potentially induce trade-off decisions or will require precedent	**2**
Project Delivery	Cost reductions arising from advancement in project delivery best practice through resource optimisation, up-front planning and analytics	**6**

Cost-Out Levers

An index of levers is provided for orientation

Table 7-2: Cost-out Levers summary list

Cost-out Lever #	Theme	Title
1	Supply Chain Maturity	Development maturity and collective industry learning
2		Construction modularisation and off-shore supply chains for assembly, prefabrication and pre-commissioning
3		Logistics benefits linked to modular scale up
4		BOP optimisation and reduction
5		Advanced construction methods reducing field hours
6	Technology Advancement	Manufacturing and assembly automation and scaleup
7		Current Density advancements
8		Innovation in materials: reduction of precious metal content
9		Electrolyser module scale increase and modular optimisation
10		Low voltage rectifier and control system advancement (insulated-gate bipolar transistors)
11		Innovation in materials: reduction of high-cost metallurgy
12		Innovation in materials: reduction in membrane thickness (PEM) / diaphragm thickness (AWE)
13		Increased electrolyser operating pressure reducing downstream system costs
14		Material substitution in piping, vessels and other equipment
15	Systems Integration	Decoupling gas purification train architecture from electrolysis
16		Medium voltage power gathering system
17	Commercial Choice	Contracting cost reduction
18		Purchase lowest cost equipment
19	Project Delivery	Digitalisation and predictive design
20		Industrial hub co-location and beneficial use of Common Use Infrastructure
21		Lean construction methods
22		Project-to-project standardisation
23		Scope minimisation to minimum technical solution (MTS) across all components
24		Streamlining of development approvals

Cost-Out Levers

24 independent cost-out levers are identified and transparent details are provided

The levers are presented over multiple pages, grouped by theme and then in decreasing cost reduction potential. The lever summaries are shown as per Figure 7-1, providing a description of the impact, the owner of the cost lever, and the context of the lever. Further information is then provided, identifying what categories will experience cost reduction, before summarising the probabilistic method and quantified results.

The **Cost-out Context** provides grounding and information linked to current applications of the cost-out lever in other areas.

The **Title** and **Description** provide details of the Cost-out Lever. This includes context and risks. The **Theme** adds context and allows grouping with similar items, and **Owner** identifies who the item impacts.

Title	Description of impact	Theme	Cost-out Context
Logistics benefits linked to modular scale up	Logistic costs of goods and equipment are a function of location and scale. Future cost reductions could arise from combining the modular pre-assembly approach with the logistics planning. Reaching sufficient scale in logistics allows participants to access different logistics models. Larger modules afford the ability to strike custom logistics agreements at lower unit cost (in $/t). This contrasts with relatively higher open-market, spot market or breakbulk models for smaller scale shipments.	Supply Chain Maturity **Owner** Developers	Larger shipments due to modular scale up directly reduce unit-cost by making different shipping models commercial.

This row indicates what categories in the **Cost Breakdown** will experience cost reductions.

Cost Breakdown													
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage	

The **probability** of each cost reduction potential eventuating for each of the low, medium and high scenarios is assigned and applied to the probabilistic modelling.

Cost Reduction Potential (%)							Distribution and Modelling	Correlation / relationship to other items
Period	2035			2050				
Probability	99%	50%	5%	99%	50%	5%		
Reference project	L	M	H	L	M	H		
RP1	1%	2%	2%	1%	2%	2%	Pert	Positive correlation to Item 2 (0.5).
RP2	1%	2%	2%	1%	2%	2%		
RP3	1%	2%	2%	1%	2%	2%		
RP4	1%	2%	2%	1%	2%	2%		

This section shows the quantified ranges of the **Cost Reduction Potential (%)** across the 2035 and 2050 period, for each of the four reference projects.

This section identifies the strength of any **Relationship** with other items identified in the cost-out levers.

Figure 7-1: Cost-out Lever summary

Cost-Out Levers

A transparent basis is provided for each of the 24 cost-out levers

The second part of the cost-out lever summary then details the calculation methodology completed for each, as shown in Figure 7-2.

The **Calculation Summary** outlines the methodology and basis that this specific cost-out lever adopted for the deterministic estimates of cost-out potential.

Calculation Summary

This cost-out lever estimates cost reductions achievable by increasing the proportion of modular (offsite) fabrication and pre-assembly, particularly in lower-cost offshore fabrication yards, compared with traditional stick-built construction at site.

The reference project cost estimate represents a balance of stick-built and modular construction methods, and estimate reflects a degree of modularisation in 2025. Modularisation is deepened in forecast years for this lever and applied to the relevant components of the estimate. These include the electrolyser balance of stack components, compression and utilities systems, as these are the areas where material gains are expected to be pronounced. This is achieved by adjusting three factors – the portion of shop hours in fabrication versus site erection, the structural bulk escalation factor and the transport cost. The adjustments are based on Worley's experience and understanding of the benefits of modularisation.

Reference project		WBS	Base case	Adjusted factor (2035 and 2050)		
				Low Savings	Central	High Savings
All	Fabrication shop hours portion	Electrolysis, compression, utilities	40%	40%	70%	80%
	Structural bulk escalation factor	Electrolysis	1	1	1.5	2
		Compression	1	1	1.24	1.65
		Utilities	1	1	1.65	2.2
	Modularisation transport cost	Electrolysis, compression, utilities	-	-	3,000	3,000

Figure 7-2: Example Cost-out Lever calculation summary

Cost-Out Lever 1

Development maturity and collective industry learning

Table 7-3: Cost-out Lever 1: Development maturity and collective industry learning

Title	Description of impact	Theme	Cost-out Context
Development maturity and collective industry learning	Cost reduction through collective industry learning reflected in pricing of components. This is a natural FOAK to NOAK transition that involves the reduction in OEM risk-pricing and contingency across suppliers. Other cost reductions will come from engineering contingencies and factors for design growth, which will be removed once projects are developed. The 'design-one-build many' concept is applied in neighbouring energy industries and could deepen cost reductions for renewable hydrogen.	Supply Chain Maturity **Owner** OEMs and Developers	Similar cost reductions occur in many analogous industries. These include solar photovoltaic power generators, and heavy industry processes.

Cost Breakdown

Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)						
Period	**2035**			**2050**		
Probability	90%	50%	5%	90%	50%	5%
Reference project	L	M	H	L	M	H
RP1	7%	13%	31%	12%	21%	40%
RP2	9%	16%	37%	15%	25%	48%
RP3	6%	10%	27%	10%	16%	36%
RP4	9%	15%	35%	15%	24%	45%

Distribution and Modelling	Correlation/relationship to other items
PertAlt	Negative correlation to Item 9 (-0.5) and Item 18 (-0.7).

Cost-Out Lever 1

Development maturity and collective industry learning

Table 7-4 : Cost-out Lever 1: Development maturity and collective industry learning

Calculation Summary

This item quantifies capital cost reductions arising from industry-wide learning. The calculation captures reductions in OEM risk pricing, engineering contingency, and manufacturing costs as cumulative installed capacity increases. The calculation applies to direct equipment contingencies and allowances, specifically the electrolyser modules, transformers and rectifiers, and gas purification equipment. Other direct and indirect cost components are held constant to avoid double counting with other levers (e.g. construction modularisation, productivity increase).

Different learning rates are applied to 2025-2035 and 2035-2050, with the initial period benefiting from higher rates due to an expected proportionally higher deployment rate. Learning rates have ben based off GenCost's (Graham, Hayward & Foster, 2025) mature technology learning rates. In effect, the degree of cost reduction is proportional to the degree of investment and production capacity increase, which is in turn dependant on global trends and external incentives.

Cost reductions are scaled from known risk allowances, contingency and design growth factors, as shown in the table on the right. These are reduced to reflect lower project and deployment risks for projects. The total cost reductions are then derived by compounding the effective learning rate over each period using the industry standard learning curve formulae dictated by Wright's Law. A simplified method, is applied to more mature equipment, such as transformers and rectifiers and gas purification equipment - the total percentage cost reductions are modified for each technology maturity.

% cost reduction from industry learning		Electrolyser modules			Rectifiers and transformers			Gas purification		
		Min	Central	Max	Min	Central	Max	Min	Central	Max
RP1	2035	16%	28%	69%	-	-	2%	-	0.5%	2%
	2050	27%	44%	87%	-	-	10%	-	2%	10%
RP2	2035	15%	26%	66%	-	-	2%	-	0.5%	2%
	2050	25%	42%	85%	-	-	10%	-	2%	10%
RP3	2035	11%	19%	53%	-	-	2%	-	0.5%	2%
	2050	18%	31%	73%	-	-	10%	-	2%	10%
RP4	2035	15%	26%	66%	-	-	2%	-	0.5%	2%
	2050	25%	42%	85%	-	-	10%	-	2%	10%

Cost-Out Lever 2

Construction modularisation and off-shore supply chains

Table 7-5: Cost-out Lever 2: Construction modularisation and off-shore supply chains for assembly, prefabrication and pre-commissioning

Title	Description of impact	Theme	Cost-out Context
Construction modularisation and off-shore supply chains for assembly, prefabrication and pre-commissioning	Renewable hydrogen production in Australia largely comprises equipment and materials procured from offshore suppliers. Cost reduction could come from deepening the level of offshore modularisation, prefabrication and performance testing conducted overseas. The works themselves occur in areas of lower cost labour, reducing costs for assembly, prefabrication and functional testing. Moreover, industrial synergies will emerge in the same regions as demand of major equipment is sustained. The future could see establishment of hydrogen industry specific fabrication and modularisation yards offshore emerging alongside developed EPC models. The overall size of the module will be limited by physical freight envelopes of dimension and/or mass; and are likely to align to major power system components. These power system components decompose into blocks of around 250 MWe today. This cost-out lever is related to other items, such as logistics benefits (Item 3), and project standardisation (Item 22).	Supply Chain Maturity **Owner** Developers	Analogous sectors, such as shipbuilding and the Oil and Gas sector have benefited from the economy of scale in the simplification of modular assembly. These industries have adopted a 'one-stop-shop' for commodities and components off-shore modularisation to the benefit of cost and deployment surety.

Cost Breakdown													
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)							Distribution and Modelling	Correlation / relationship to other items
Period	**2035**			**2050**				
Probability	99%	50%	5%	99%	50%	5%		
Reference Project	**L**	**M**	**H**	**L**	**M**	**H**		
RP1	-	0.02%	0.7%	-	0.02%	0.7%	Pert	Positive correlation to Item 3 (0.5), Item 22 (0.5), Item 23 (0.5) and Item 24 (0.5).
RP2	-	0.8%	1.3%	-	0.8%	1.3%		
RP3	-	1.0%	1.9%	-	1.0%	1.9%		
RP4	-	1.2%	1.9%	-	1.2%	1.9%		

Cost-Out Lever 2

Construction modularisation and off-shore supply chains

Table 7-6: Cost-out Lever 2: Construction modularisation and off-shore supply chains for assembly, prefabrication and pre-commissioning

Calculation Summary

This cost-out lever estimates cost reductions achievable by increasing the proportion of modular (offsite) fabrication and pre-assembly, particularly in lower-cost offshore fabrication yards, compared with traditional stick-built construction at site.

Note that this lever a trade-off to some extent: deeper modularisation requires additional structural material and will incur freight costs on a different basis. The trade-off between these factors is represented numerically in the table below. The savings (net of the trade-off) are on the previous page, and while modest, modular thinking enables a range of related savings (advanced construction, standardisation etc.)

The reference project cost estimate represents a balance of stick-built and modular construction methods, and estimate reflects a degree of modularisation in 2025. Modularisation is deepened in forecast years for this lever and applied to the relevant components of the estimate. These include the electrolyser balance of stack components, compression and utilities systems, as these are the areas where material gains are expected to be pronounced. This is achieved by adjusting three factors – the portion of shop hours in fabrication versus site erection, the structural bulk escalation factor and the transport cost. The adjustments are based on Worley's experience and understanding of the benefits of modularisation.

Reference project		WBS	Base case	Adjusted factor (2035 and 2050)		
				Low Savings	Central	High Savings
All	Fabrication shop hours portion	Electrolysis, compression, utilities	40%	40%	70%	80%
	Structural bulk escalation factor	Electrolysis	1	1	1.5	2
		Compression	1	1	1.24	1.65
		Utilities	1	1	1.65	2.2
	Additional transport cost for large module	Electrolysis, compression, utilities	-	-	3,000 AUD/t	3,000 AUD/t

Cost-Out Lever 3

Logistics benefits linked to modular scale up

Table 7-7: Cost-out Lever 3: Logistics benefits linked to modular scale up

Title	Description of impact	Theme	Cost-out Context
Logistics benefits linked to modular scale up	Logistic costs of goods and equipment are a function of location and scale. Future cost reductions could arise from combining the modular pre-assembly approach with the logistics planning. Reaching sufficient scale in logistics allows participants to access different logistics models. Larger modules afford the ability to strike custom logistics agreements at lower unit cost (in $/t). This contrasts with relatively higher open-market, spot market or breakbulk models for smaller scale shipments.	Supply Chain Maturity **Owner** Developers	Larger shipments due to modular scale up directly reduce unit-cost by making different shipping models commercial.

Cost Breakdown												
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)							Distribution and Modelling	Correlation / relationship to other items
Period	**2035**			**2050**				
Probability	99%	50%	5%	99%	50%	5%		
Reference project	L	M	H	L	M	H		
RP1	1%	2%	2%	1%	2%	2%	Pert	Positive correlation to Item 2 (0.5).
RP2	1%	2%	2%	1%	2%	2%		
RP3	1%	2%	2%	1%	2%	2%		
RP4	1%	2%	2%	1%	2%	2%		

Cost-Out Lever 3

Logistics benefits linked to modular scale up

Table 7-8: Cost-out Lever 3: Logistics benefits linked to modular scale up

Calculation Summary
This lever estimates cost reductions arising from logistics efficiencies enabled by large-scale modularisation, rather than from modularisation itself (which is addressed separately in Item 2). Improvements from this item are not predicted to deepen beyond 2035, and predictions in 2035 and 2050 cases are same. The benefit of sourcing components nearby to where the modules are constructed is accounted for by applying a reduction to the unit-freight costs for the relevant equipment. This includes the electrolysers, compression, waste heat recovery (for SOEC) and utilities. All other costs are kept constant in this lever. Lower unit-freight costs (usually by tonne) are available to larger modules as logistics transition from breakbulk or spot-cargo pricing to bespoke logistics contracts that yield benefits of scale. The base freight allowance is 8% for all reference projects. This was reduced to 5% for all applicable WBS items for the central case. The low and high savings cases were calculated using a nominal change in the central case savings of -35% and +5% respectively. This is based on Worley's freight cost data, and experience in estimating cost in similar applications.

Cost-Out Lever 4

BOP optimisation and reduction

Table 7-9: Cost-out Lever 4: BOP optimisation and reduction

Title	Description of impact	Theme	Cost-out Context
BOP optimisation and reduction	Hydrogen production by electrolysis remains a nascent industry, the largest facility at the time of writing is a ~475 MWe alkaline facility in China. As the designs evolve, and research is included in next-generation systems there will be a progressive optimisation of the balance of plant component of costs. Specific examples include the scale of cooling systems required as electrolysis efficiency improves - a more efficient unit rejects energy as heat, and cost reduction as capital costs for components decrease.	Supply Chain Maturity **Owner** OEMs and Developers	This is a direct cost reduction through the removal, downscaling and capital efficiency of equipment. As the efficiency of electrolysis improves, cooling systems will reduce in scale. Other systems will be optimised to minimise plot space aligned with modularisation and improvements to construction method (separate items).

Cost Breakdown

Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)							Distribution and Modelling	Correlation / relationship to other items
Period	**2035**			**2050**				
Probability	95%	50%	5%	95%	50%	5%		
Reference project	L	M	H	L	M	H		
RP1	-	0.1%	0.2%	-	0.2%	0.4%	Pert	Related to item 23
RP2	3%	3%	4%	4%	4%	4%		
RP3	3%	4%	4%	4%	4%	5%		
RP4	3%	3%	4%	4%	4%	4%		

Cost-Out Lever 4

BOP optimisation and reduction

Table 7-10: Cost-out Lever 4: BOP optimisation and reduction

Calculation Summary

This lever estimates potential cost reduction for BOP systems (this does not include gas purification systems, which are considered in other levers). This lever is intended to reflect a scenario where the size, layout and number of equipment items and the degree of commonality and integration are optimised.
The lever also reflects reducing capital cost trends in BOP components (H_2 compressors and BESS for example).
In this calculation, the impacts affect all reference projects but are limited to the BOP systems that are considered most likely to benefit from this improvement:

- BESS and compression, due to the technology advancements and rapidly increasing scale of production
- Utility systems, due to the potential reduction in scale of cooling systems as electrolyser efficiency improves.

The cost reduction scenarios are calculated as reductions to the installed cost of the relevant BOP items – these are listed in the table below.
Compression reductions are based on internal cost data and Worley's own analysis given the maturity of the technologies. The utilities reductions for the central case assume that cooling systems comprises around half of utility costs across OEMs, and that the electrolyser cooling duty will might be halve by 2050.

Reference project	WBS	Base	Installed cost reduction (2035)			Installed cost reduction (2050)		
			Low Savings	Central	High Savings	Low Savings	Central	High Savings
All	BESS	100%	60%	70%	80%	80%	85%	90%
	Compression	100%	-	2.5%	5%	-	5%	10%
	Utilities	100%	-	7%	10%	5%	17%	25%

Cost-Out Lever 5

Advanced construction methods reducing field hours

Table 7-11: Cost-out Lever 5: Advanced construction methods reducing field hours

Title	Description of impact	Theme	Cost-out Context
Advanced construction methods reducing field hours	Construction of hydrogen production facilities requires a range of methodologies and practices. Cost reduction could come from advanced design practices that reduce the time to construct, resulting in fewer site hours that incur a premium cost. Advanced design practices include: • Designing to locate services and utilities out of the ground and onto modules. • Reduce extent of civil on site through reduction of footprint, optimisation of loads and precast foundations. This minimises formwork and concrete volumes and hence site works. • Deeper application of robotics and automated construction methods throughout construction (such as human replacement with similarly capable robots operating machinery, adoption of automated 3D printing techniques etc.).	Supply Chain Maturity **Owner** Developers	This is a direct cost reduction through minimising high-cost labour on site hours.

Cost Breakdown												
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)							Distribution and Modelling	Correlation / relationship to other items
Period	**2035**			**2050**				
Probability	99%	50%	20%	99%	50%	20%		
Reference project	L	M	H	L	M	H		
RP1	-	0.3%	0.6%	0.3%	1.0%	2.2%	Pert	Negative correlation to Item 21 (-0.7).
RP2	-	0.3%	0.8%	0.3%	1.1%	2.5%		
RP3	-	0.3%	0.9%	0.3%	1.6%	3.1%		
RP4	-	0.5%	1.1%	0.5%	1.4%	3.1%		

Cost-Out Lever 5

Advanced construction methods reducing field hours

Table 7-12: Cost-out Lever 5: Advanced construction methods reducing field hours

Calculation Summary

This lever reduces costs through improvements in on-site construction productivity driven by advanced methods and automation (digitalisation and labour productivity improvements arising from lean construction methods are separate items). The calculation methodology reduces cost for on-site activities, which are measured by 'Install / Construct' outcomes in the reference estimates.

Advanced construction methods (such as deepening of robotics and automation) expects the same output on site for fewer staff hours. Worley's interpretation of construction workforce productivity in Australia informs our interpretation of minimum and central productivity gains. The high-savings case productivity gain is substantially higher due to the factors noted in Table 7-11, particularly the application of robotics or remote activities.

Adjustments are applied to the site labour and productivity factors for all project estimates. The factors used and the applicable WBS items are listed in the table below.

Reference project	WBS	Base factor	Adjusted factor (2035)			Adjusted factor (2050)			Factor
			Low Savings	Central	High Savings	Low Savings	Central	High Savings	
All	Power systems and, BESS	20%	20%	20%	17.5%	20%	20%	15%	Fraction site erection
All	Compression, utilities	1.00	1.00	0.98	0.95	0.98	0.90	0.80	Productivity adjustment
All	WHRU/Steam	1.20	1.20	1.18	1.15	1.18	1.10	1.00	Productivity adjustment
1, 2, 3	Electrolysis	1.00	1.00	0.98	0.95	0.98	0.90	0.80	Site erection
4	Electrolysis	0.90	0.90	0.88	0.86	0.88	0.81	0.72	Site erection

Cost-Out Lever 6

Manufacturing and assembly automation and scaleup (fabrication yard and OEMs)

Table 7-13: Cost-out Lever 6: Manufacturing and assembly automation and scaleup

Title	Description of impact	Theme	Cost-out Context
Manufacturing and assembly automation and scaleup	Equipment for hydrogen production is manufactured and assembled by a range of processes, supported by a range of manufacturing practices. These processes and practices exist today in a state of pseudo-equilibrium with the rate of technology development and ultimate demand for the goods. Sustained demand for hydrogen production equipment of all kinds will deepen the application of advanced manufacturing in the production of equipment. The modular electrolysis and modularised unit approach (repeated units) are particularly well suited to cost reduction through automation, replication and mechanisation of manufacturing processes. Cost reductions will arise through increased automation, repeatable with a lower labour fraction, and efficiencies of scale in manufacturing.	Technology Advancement **Owner** OEMs	A direct analogue for this lever is in the expanded mechanisation of battery electric storage allowing lower cost, and larger scale in recent years.

Cost Breakdown												
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)						
Period	**2035**			**2050**		
Probability	99%	50%	15%	99%	50%	15%
Reference project	L	M	H	L	M	H
RP1	0.01%	0.01%	0.05%	0.03%	0.1%	0.3%
RP2	0.004%	0.01%	0.04%	0.02%	0.1%	0.2%
RP3	0.01%	0.01%	0.06%	0.03%	0.4%	0.6%
RP4	0.3%	0.3%	0.3%	0.3%	0.3%	0.5%

Distribution and Modelling	Correlation / relationship to other items
Pert	-

Cost-Out Lever 6

Manufacturing and assembly automation and scaleup

Table 7-14: Cost-out Lever 6: Manufacturing and assembly automation and scaleup

Calculation Summary

This lever reduces costs by minimising fabrication labour (an offsite activity) and relies on deepening automation and mechanisation to increase manufacturing productivity. While the lever covers both automation and scale-up, cost savings from the latter are already encapsulated within lever 1 (development maturity and collective learning), and hence these savings are excluded from this analysis.

Electrolyser stacks are already produced in multi-GW/yr production facilities by OEMs with a varying degrees robotic assembly. The reduction potential tabulated below reflects future expectations for electrolyser stacks building on this baseline.

The reduction potential for modular assembly of other components (stack, separator, pumps, piping etc.), is also expected to be automated further.
This automation is applied by adjusting the base fabrication productivity factor, which sets the labour hours required per weight of the equipment. However, as increased automation would come at an additional capital cost investment, these gross productivity improvements are dampened. The dampened factors used in the calculation of this lever are listed in the table below. These are based on Worley's experience and understanding of fabrication methods and potential improvement. No change is made to other indirect costs by this lever (freight, spares, engineering, etc.).

Reference project	WBS	Base factor	Adjusted productivity factor (2035) Fabrication yard and equip assembly			Adjusted productivity factor (2050) Fabrication yard and equip assembly		
			Low Savings	Central	High Savings	Low Savings	Central	High Savings
1, 2, 3	Electrolysis, utilities	1.00	0.996	0.99	0.96	0.98	0.95	0.80
3	Compression	1.00	0.996	0.99	0.96	0.98	0.95	0.80
4	Electrolysis	0.90	0.896	0.89	0.86	0.88	0.86	0.72
	Utilities	1.00	0.996	0.99	0.96	0.98	0.95	0.80

Cost-Out Lever 7

Current density advancements

Table 7-15: Cost-out Lever 7: Current density advancements

Title	Description of impact	Theme	Cost-out Context
Current density advancements	Electrolysers pass electrical energy through electrodes and increasing the energy flux at the surface of the electrode, measured in A/cm^2 is an existing area of research and development. Cost reductions are expected to arise from increasing the feasible current density and thus reducing the area of the stacks and membranes. This is an active area of research, both in reducing the area and with avoiding an impact on efficiency. This study includes this item as it will also result in a reduction of electrolysis area per kWe deployed.	Technology Advancement **Owner** OEMs	This cost-out lever reduces the size of the membranes, and hence quantity of materials required, and physical space occupied for each unit.

Cost Breakdown												
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)						
Period	**2035**			**2050**		
Probability	85%	50%	10%	85%	50%	10%
Reference project	L	M	H	L	M	H
RP1	3%	4%	5%	5%	6%	7%
RP2	3%	5%	8%	8%	9%	10%
RP3	4%	5%	6%	6%	7%	7%
RP4	3%	5%	8%	8%	9%	11%

Distribution and Modelling	Correlation / relationship to other items
Pert	-

Cost-Out Lever 7

Current density advancements

Table 7-16: Cost-out Lever 7: Current density advancements

Calculation Summary

This lever estimates equipment cost reductions arising from improvements in electrolyser current density. The calculation only impacts the electrolyser stack components that have cost which scales with active area. These are the porous transport layers, structural layers, bipolar plates (BPs) and the diaphragm/membrane. The basis for current density improvement were obtained from Sungrow (2024), Huadian (2025) and US Department of Energy. (2022.1).

The expected increase in current density for each scenario by 2035 and 2050, in the first table below, is based on various public literature sources, and Worley's insight from engagement with electrolyser OEMs. The total stack area reductions due to these current density improvements were then determined relative to the base densities. The portion of the electrolyser costs deemed sensitive to current density increases were estimated using the AWE and PEM cost breakdowns in IRENA's Green Hydrogen Cost Reduction report (IRENA, 2020). The estimates were 30% and 40% respectively for AWE and PEM. In the absence of a similar references for SOEC, a figure of 20% was adopted. The total cost reductions are a product of the stack area reduction and the total contribution of the components to the cost (note while current density is OEM specific, the cost lever value is in the trend and ratio of improvements).

Technology	Base	Current density, A/cm² (2035)			Current density, A/cm² (2050)		
		Low Savings	Central	High Savings	Low Savings	Central	High Savings
SOEC	1	1.4	1.5	1.8	2	2.25	3
PEM	2	2.5	3	4	4	4.5	6
AWE	0.3	0.6	0.75	0.9	0.9	1.4	1.8

Reference project	Technology	Equipment cost reduction (2035)			Equipment cost reduction (2050)		
		Low Savings	Central	High Savings	Low Savings	Central	High Savings
1	SOEC	11%	13%	18%	20%	22%	27%
2, 4	PEM	10%	16%	24%	24%	26%	32%
3	AWE	17%	21%	23%	23%	28%	29%

Cost-Out Lever 8

Innovation in materials: reduction of precious metal content

Table 7-17: Cost-out Lever 8: Innovation in materials: reduction of precious metal content

Title	Description of impact	Theme	Cost-out Context
Innovation in materials: reduction of precious metal content	Electrolyser modules use precious and/or scarce metals (such as platinum, iridium or gold) for a range of reasons, such as corrosion reduction or improved reaction kinetics. These precious metals comprise a relatively large fraction of equipment costs. Cost reduction will arise from reducing the volume of metal needed through optimisation, or substitution away from, the precious and/or scarce materials.	Technology Advancement **Owner** OEMs	This directly reduces cost by reducing expensive raw materials.

Cost Breakdown													
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)						
Period	**2035**			**2050**		
Probability	80%	50%	1%	80%	50%	1%
Reference project	L	M	H	L	M	H
RP1	-	-	-	-	-	-
RP2	2%	2%	3%	3%	3%	3%
RP3	-	-	-	-	-	-
RP4	2%	3%	3%	3%	3%	3%

Distribution and Modelling	Correlation / relationship to other items
Pert	-

Cost-Out Lever 8

Innovation in materials: reduction of precious metal content

Table 7-18: Cost-out Lever 8: Innovation in materials: reduction of precious metal content

Calculation Summary

This cost out lever estimates the potential reduction in cost that can be achieved by decreasing platinum group metal (PGM) content in electrolyser stacks. This lever applies only to reference projects 2 and 4, which use PEM as their electrolysis technology - SOEC and alkaline electrolysers generally do not use PGMs. The cost reductions impact the electrolyser (WBS 1310) equipment cost only.

The calculation uses the US Department of Energy (2022.2) data on the current and target future PGM content of electrolysers to determine PGM reductions:

- 2022 status: 0.8 g/kW
- 2026 target: 0.1 g/kW
- Ultimate target: 0.03 g/kW.

The value of the PGMs used are based on market price data from late 2025. The potential mass reduction is combined with the value of the metal and the estimated contribution of each metal to determine the possible cost reduction. The US DOE targets and PGM data provide the basis for the reduction scenarios for 2035 and 2050. The PGM reductions are the estimated PGM usage values subtracted from the 2026 basis, which is taken as the US DOE reported 2022 status of 0.8 g/kW. Note while PGM content is OEM specific, the cost lever value is in the trend of improvements.

PGM	Content by mass	Value (AUD/g)
Platinum	23%	$115
Palladium	23%	$95
Iridium	54%	$250

Year	Case	PGM usage (g/kW)	Equipment cost reduction ($m/MW)
2035	Low Savings	0.20	0.109
	Central	0.10	0.128
	High Savings	0.06	0.135
2050	Low Savings	0.06	0.135
	Central	0.03	0.140
	High Savings	0.02	0.142

Cost-Out Lever 9

Electrolyser module scale increase and modular optimisation

Table 7-19: Cost-out Lever 9: Electrolyser module scale increase and modular optimisation

Title	Description of impact	Theme	Cost-out Context
Electrolyser module scale increase and modular optimisation	Commercial scale hydrogen production at the scale indicated in this study's reference projects comprises multiple repeated sub-units (i.e. cells, stacks and modules). Cost reductions are expected as the scale of each sub-unit increases. This increase would necessarily result in simpler system architecture with fewer interfaces and a lower total cost when measured in $/kWe.	Technology Advancement **Owner** OEMs	Cost efficiency of scale will emerge, analogous to other energy industry sectors. Note that a maximum scale of the sub-unit architecture is likely to be aligned to established power system sub-units, which are around 250 MWe.

Cost Breakdown												
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)						
Period	**2035**			**2050**		
Probability	99%	50%	1%	99%	50%	1%
Reference project	L	M	H	L	M	H
RP1	-	-	-	-	-	-
RP2	-	6%	12%	-	12%	24%
RP3	-	5%	10%	-	10%	21%
RP4	-	6%	12%	-	12%	23%

Distribution and Modelling	Correlation / relationship to other items
Pert	Negative correlation to Item 1 (-0.5).

Cost-Out Lever 9

Electrolyser module scale increase and modular optimisation

Table 7-20: Cost-out Lever 9: Electrolyser module scale increase and modular optimisation

Calculation Summary

Electrolyser stacks are typically between 1-5 MW currently for PEM and AWE (largest installation being a 10 MW PEM stack), and <25 kW for SOEC. There are technical and operational limitations to increasing the stack size. This item specifically increases the modular size of combined stacks. Some electrolyser modules are being offered at sizes up to or around 20 MW, containing multiple stacks. If the total kWe of the module is increased via bigger or more stacks, the number of larger modules installed would be smaller for the same capacity. This reduces equipment count which reduces both the direct costs (e.g. equipment, procurement, construction/installation) and indirect (e.g. engineering and installation) costs. This cost-out lever seeks to determine the potential cost reduction from this. The % cost reduction is calculated by subtracting the module unit cost divided by the module size from the reference cost:

% cost reduction = 1 – (Module unit cost / Module size)

The following scenarios were developed for reference projects 2, 3 and 4 and compared to the base configuration of 10 x 20 MW modules in each 200 MW hydrogen production train. The scenarios apply reductions to the equipment item costs for both the electrolyser modules (WBS 1310) and electrical equipment (WBS 1320) based on nominal increased module sizes. SOEC is very immature technology and has issues with high temperature piping/material/equipment, which are inherently more difficult to manufacture at scale. Increased module sizes are not expected to have a material impact on the overall costs for SOEC. SOEC will require multiple large-scale projects to drive the maturity forward, which is not forecasted to occur in the relative short term. Due to this immaturity of SOEC electrolysers therefore, reference project 1 was excluded.

Reference project	Cost Reduction (2035)			Cost Reduction (2050)		
	Low Savings	Central	High Savings	Low Savings	Central	High Savings
2, 3, 4	-	25 MW modules (1.25 x module size) 1.1 x module unit cost **12% reduction**	40 MW modules (2 x module size) 1.5 x module unit cost **25% reduction**	-	40 MW modules (2 x module size) 1.5 x module unit cost **25% reduction**	40 MW modules (2 x module size) 1 x module unit cost **50% reduction**

Cost-Out Lever 10

Low voltage rectifier and control system advancement (insulated-gate bipolar transistors)

Table 7-21: Cost-out Lever 10: Low voltage rectifier and control system advancement (insulated-gate bipolar transistors)

Title	Description of impact	Theme	Cost-out Context
Low voltage rectifier and control system advancement (insulated-gate bipolar transistors)	The use of thyristor-based rectifiers introduces disturbances in power networks. These disturbances require compensation and represent cost elements (such as STATCOM or Static Var Compensation). Insulated gate bipolar transistors (IGBT) based rectifiers provide active compensation, not only removing the need for the compensation equipment, but it also improves the efficiency of the electrical distribution within the plant. The scale of IGBT rectifiers is increasing, and units are up to 5MW size at the time of writing. The practical maximum scale of these rectifiers corresponds to a maximum module scale of 10 MW (below the scale of the reference projects adopted for this study). As the maximum practical scale increases, the corresponding electrolyser package size that makes use of this technology will increase above 10 MW.	Technology Advancement **Owner** OEMs	This is a direct cost reduction which trades higher rectifier costs for the removal of other expensive power equipment.

Cost Breakdown												
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)						
Period	**2035**			**2050**		
Probability	70%	50%	30%	70%	50%	30%
Reference project	L	M	H	L	M	H
RP1	-	-	-	-	-	-
RP2	-	-	-	9%	11%	13%
RP3	-	-	-	10%	12%	14%
RP4	-	-	-	10%	12%	14%

Distribution and Modelling	Correlation / relationship to other items
Pert	-

Cost-Out Lever 10

Low voltage rectifier and control system advancement (insulated-gate bipolar transistors)

Table 7-22: Cost-out Lever 10: Low voltage rectifier and control system advancement (insulated-gate bipolar transistors)

Calculation Summary
Hydrogen production facilities are large electricity consumers when compared to other users. To maintain grid stability for both islanded, local and project grids, the hydrogen production facilities include equipment to maintain stability across the entire range of project operating and failure scenarios. This applies to both renewable islanded projects (private grid), and for grid connected projects. IGBT type rectifiers do not adversely affect grid stability, though they are more expensive than the dominant thyristor technology today. This item estimates cost reduction by switching from thyristor to IGBT type rectifiers and removal, and hence savings, on synchronous compensation equipment that is not required. The IGBT rectifiers are more expensive than thyristors, but the nett project cost is lower. This lever quantifies the savings as the installed cost of the electrical equipment that is not required for IGBT rectifiers - the harmonic filter, STATCOM and associated transformer and rectifier – assuming cost parity between IGBT and conventional rectifiers. As IGBTs today are small scale, and relatively expensive. This cost-out lever expects savings only in 2050. Reference project 1 is also excluded from the analysis due to the low deployment of SOECs. The equipment costs are based on real-world vendor data for a mid-scale hydrogen project. Equipment costs were escalated to 2025 costs and scaled to the reference project sizes. Typical allowances for the relevant direct and indirect costs were added to obtain the installed cost. This installed cost represents the central case. As the source data was based on a previous project estimate, the low and high savings cases are related to the estimate accuracy range: • Low Savings Case: 15% TIC reduction from the central case • Central Case: TIC estimate reduction for IGBTs based on past project • High Savings Case: 20% TIC increase from the central case The magnitude of the saving relies heavily on the assumption that IGBT rectifiers increase in scale and decrease in cost by 2050.

Cost-Out Lever 11

Innovation in materials: reduction of high-cost metallurgy

Table 7-23: Cost-out Lever 11: Innovation in materials: reduction of high-cost metallurgy

Title	Description of impact	Theme	Cost-out Context
Innovation in materials: reduction of high-cost metallurgy	Electrolyser modules make use of specialised materials that introduce cost through their difficulty to machine (such as titanium or ceramics) are inherent cost (corrosion resistant materials). These are used primarily in highly corrosive or highly erosive environments. Cost reductions will arise from reduction, optimisation or substitution away from these materials and introduction of alternatives in the same service.	Technology Advancement **Owner** OEMs	This directly reduces cost by reducing moderately expensive raw materials, and costs associated with the machining and manufacture of these units.

Cost Breakdown												
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)							Distribution and Modelling	Correlation / relationship to other items
Period	**2035**			**2050**				
Probability	99%	50%	1%	99%	50%	1%		
Reference project	L	M	H	L	M	H		
RP1	-	2%	3%	2%	3%	5%	Pert	-
RP2	-	2%	4%	2%	4%	6%		
RP3	-	-	-	-	-	-		
RP4	-	2%	4%	2%	4%	6%		

Cost-Out Lever 11

Innovation in materials: reduction of high-cost metallurgy

Table 7-24: Cost-out Lever 11: Innovation in materials: reduction of high-cost metallurgy

Calculation Summary

This lever estimates future cost reduction associated with the materials that are expensive to machine and construct (such as titanium and ceramics). These materials are used various components of the electrolyser stacks. This lever encompasses both material use reduction and alternative cheaper materials and construction technologies. This analysis considers the larger cost components and does not include precious metals, which are covered in Item 8. PEM and SOEC electrolyser materials vary with the licensor and OEM, however they are typically constructed with the following materials. AWE (reference project 3) uses primarily nickel and stainless steel and is therefore excluded.

PEM:

- Porous transport layer (PTL) – Titanium
- Bipolar plate (BP) – Titanium

SOEC:

- PTL – Nickel
- BP – Stainless Steel
- Electrolyte – Ceramic

IRENA's (2020) report is used as a basis to determine the contribution of equipment containing high-cost metals as part of the overall electrolyser equipment cost[1]. For PEM, this figure indicates that the PTL and BP components are 32% of the total cost. Due to the immaturity of SOECs and lack of publicly available literature on cost breakdowns, a similar contribution was assumed for SOEC. Cost reduction scenarios were then developed by quantifying reductions to the relevant portion of the electrolyser equipment cost (WBS 1310) only – other direct costs and indirect costs remain constant.

Reference project	Equipment Cost Reduction (2035)			Equipment Cost Reduction (2050)		
	Low Savings	Central	High Savings	Low Savings	Central	High Savings
1	-	3%	6%	3%	6%	10%
2, 4	-	3%	6%	3%	6%	10%

Cost-Out Lever 12

Innovation in materials: reduction in membrane thickness (PEM) / diaphragm thickness (AWE)

Table 7-25: Cost-out Lever 12: Innovation in materials: reduction in membrane thickness (PEM) / diaphragm thickness (AWE)

Title	Description of impact	Theme	Cost-out Context
Innovation in materials: reduction in membrane thickness (PEM) / diaphragm thickness (AWE)	PEM and AWE electrolysers use membranes and diaphragms that are expensive to manufacture and contribute a considerable fraction of the stack cost. PEM electrolysers use polymer membranes and alkaline electrolysers use porous inorganic diaphragms. Cost reduction could come through the reduction of the membrane or diaphragm thickness. This would directly lower material cost and can improve current density (refer to Item 8). This reduction in thickness must maintain durability and proton conductivity and prevent crossover of the produced gases.	Technology Advancement **Owner** OEMs	This directly reduces cost by reducing expensive raw materials, and costs associated with the machining and manufacture of these units.

Cost Breakdown												
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)						
Period	**2035**			**2050**		
Probability	99%	50%	1%	99%	50%	1%
Reference project	L	M	H	L	M	H
RP1	-	-	-	-	-	-
RP2	-	0.2%	0.4%	0.4%	0.5%	0.6%
RP3	-	0.2%	0.4%	0.4%	0.6%	0.8%
RP4	-	0.2%	0.3%	0.3%	0.5%	0.6%

Distribution and Modelling	Correlation / relationship to other items
Pert	-

Cost-Out Lever 12

Innovation in materials: reduction in membrane thickness (PEM) / diaphragm thickness (AWE)

Table 7-26: Cost-out Lever 12: Innovation in materials: reduction in membrane thickness (PEM) / diaphragm thickness (AWE)

Calculation Summary

This cost out lever estimates potential cost savings by reducing the electrolyser diaphragm (or membrane) thickness through improvements in factors such as manufacturing practices, performance and/or material advancements. For this cost-out lever, the diaphragm or membrane assessment excludes precious metal catalyst coatings or content, which are addressed in Item 8.

Commercial AWE diaphragms are currently up to 460 μm (IRENA, 2020), while PEM membranes are typically between 125 - 200 μm (Park et al., 2020). Literature suggests technology improvements could see AWE and PEM reduced to below 50 and 20 μm respectively (IRENA, 2020). SOEC OEMs are already offering electrolyte membrane thicknesses as low as 3-6 μm (Nexceris, 2025) and reference project 1 is excluded from this lever. Lowering membrane thickness significantly increases gas permeation and hence a lower limit exists for all electrolyser technologies to maintain safety and durability.

IRENA also indicate the contributions of the diaphragm and membrane to the electrolyser equipment cost. These contributions are 2% for PEM and 4% for AWE. Worley developed specific cost reduction fractions between 0.6% and 3.2% on the basis that the reduction in membrane thickness is directly proportional to the reduction in relevant cost fractions. Details are below:

Reference project	Equipment Cost Reduction (2035) and associated assumed membrane thickness			Equipment Cost Reduction (2050) and associated assumed membrane thickness		
	Low Savings	Central	High Savings	Low Savings	Central	High Savings
2, 4	200 μm No savings	150 μm **0.6% reduction**	100 μm **1.1% reduction**	100 μm **1.1% reduction**	50 μm **1.7% reduction**	20 μm **2.0% reduction**
3	460 μm No savings	345 μm **0.9% reduction**	230 μm **1.8% reduction**	230 μm **1.8% reduction**	115 μm **2.7% reduction**	46 μm **3.2% reduction**

TIC savings from this lever are almost negligible. The primary benefit of development in this area is in operating cost savings, as reduced membrane thickness improves electrical efficiency by lowering the ohmic resistance.

Cost-Out Lever 13

Increased electrolyser operating pressure reducing downstream system costs

Table 7-27: Cost-out Lever 13: Increased electrolyser operating pressure reducing downstream system costs

Title	Description of impact	Theme	Cost-out Context
Increased electrolyser operating pressure reducing downstream system costs	Commercial electrolysers today operate between just above ambient pressure and 30 barg. Cost reductions could arise from the increase of the electrolyser operating pressure which reduces the scale of compression systems downstream. This will reduce the size of downstream equipment, and piping. Note that this must be contrasted with an increase in cost for the electrolyser unit(s) to operate at higher pressure and applies to SOEC and Alkaline units, which are the lower pressure electrolysis technologies today.	Technology Advancement **Owner** OEMs	This is a direct cost reduction trading the inclusion of compression equipment for the ability of electrolysers to retain and operate at elevated pressure.

Cost Breakdown												
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)							Distribution and Modelling	Correlation / relationship to other items
Period	**2035**			**2050**				
Probability	90%	50%	10%	90%	50%	10%		
Reference project	L	M	H	L	M	H		
RP1	10%	11%	11%	10%	11%	11%	Pert	-
RP2	-	-	-	-	-	-		
RP3	6%	7%	7%	6%	7%	7%		
RP4	-	-	-	-	-	-		

Cost-Out Lever 13

Increased electrolyser operating pressure reducing downstream system costs

Table 7-28: Cost-out Lever 13: Increased electrolyser operating pressure reducing downstream system costs

Calculation Summary

This lever assesses the potential cost reduction from increasing the electrolyser operating pressure such that no downstream compression is required. This applies to reference project 1 and 3 only, as both SOEC and AWE reference technologies in this study operate at low pressure and include H2 compression to the baseline 30barg.

The cost reduction is estimated by removing the installed cost of the hydrogen compressors offset against an allowance for increase in the electrolyser equipment cost (WBS 1310). This allowance is to account for the additional cost of the higher pressure rated equipment (stack, vessels, piping, etc.) compared to that of a low-pressure electrolyser.

The cost reduction scenarios are the same for 2035 and 2050, as the savings are not expected to deepen beyond 2035.

Reference project	WBS	Cost Reduction (2035 and 2050)		
		Low Savings	Central	High Savings
1,3	Electrolyser	5% equipment cost increase	2% equipment cost increase	1% equipment cost increase
1,3	Compression	100% cost reduction	100% cost reduction	100% cost reduction

Cost-Out Lever 14

Material substitution in piping, vessels and other equipment

Table 7-29: Cost-out Lever 14: Material substitution in piping, vessels and other equipment

Title	Description of impact	Theme	Cost-out Context
Material substitution in piping, vessels and other equipment	The material of construction for piping is dependent on a variety of factors (such as pressure retention, chemical compatibility, corrosion resistance and many others). Cost reductions are already apparent in piping material optimisations, and this will extend into other areas of module design. Specifically: • for piping or vessels not in hydrogen service there is a potential to use HDPE/GRP or other low-cost alternatives to ASME B31.3 or other ASME steel piping, and • For piping or vessels in hydrogen service reinforced thermoplastic materials may substitute ASME B31.12 steel piping.	Technology Advancement **Owner** Developers	This is a direct cost reduction which reduces material cost and is a current practice by some OEMs. ThyssenKrupp substitute some piping and vessels for suitable alternatives today.

Cost Breakdown												
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)						
Period	**2035**			**2050**		
Probability	90%	50%	10%	90%	50%	10%
Reference project	L	M	H	L	M	H
RP1	0.03%	0.09%	0.12%	0.03%	0.09%	0.12%
RP2	0.02%	0.06%	0.09%	0.02%	0.06%	0.09%
RP3	0.03%	0.07%	0.09%	0.03%	0.07%	0.09%
RP4	0.02%	0.05%	0.07%	0.02%	0.05%	0.07%

Distribution and Modelling	Correlation / relationship to other items
Pert	-

Cost-Out Lever 14

Material substitution in piping, vessels and other equipment

Table 7-30: Cost-out Lever 14: Material substitution in piping, vessels and other equipment

Calculation Summary

This item estimates future potential cost reduction in bulk equipment costs by replacing the carbon steel piping in the utilities systems with alternative materials.

The material substitution is applied to all utilities systems except for the nitrogen, instrument air and flare/vent systems, which require higher strength and pressure rated materials alternative materials are expected to offer in 2035 or 2050. The difference in cost due to the substitution is assessed by applying the nominal reductions in the table below to the impacted pipe material unit cost. All other direct costs (construction, fabrication) and freight costs are impacted by this reduction. The approach is unchanging from 2035 to 2050 and across all reference projects.

Reference project	Utility Piping unit cost reduction (2035 and 2050)		
	Low Savings	Central	High Savings
All	20%	50%	70%

The TIC savings from this lever are modest, due to the already low proportion of the project TIC attributed to utilities.

Cost-Out Lever 15

Decoupling gas purification train architecture from electrolysis

Table 7-31: Cost-out Lever 15: Decoupling gas purification train architecture from electrolysis

Title	Description of impact	Theme	Cost-out Context
Decoupling gas purification train architecture from electrolysis	Gas purification systems are commonly developed separately to electrolysis stack architecture. Decoupling the purification train from the electrolysis train could expand and optimise gas purification in a separate train architecture to the electrolysis modules. This will ultimately be limited by engineering fundamentals, such as gas volume flow limits or maximum vessel size practicalities.	Systems Integration **Owner** Developers	Optimisation of the train architecture will reduce cost directly through reduction of unit equipment scale, and right-sizing modules.

Cost Breakdown											
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)						
Period	**2035**			**2050**		
Probability	90%	50%	10%	90%	50%	10%
Reference project	L	M	H	L	M	H
RP1	-	-	-	-	-	-
RP2	0.3%	0.5%	0.6%	0.3%	0.5%	0.6%
RP3	0.3%	0.5%	0.7%	0.3%	0.5%	0.7%
RP4	0.3%	0.5%	0.6%	0.3%	0.5%	0.6%

Distribution and Modelling	Correlation / relationship to other items
Pert	-

Cost-Out Lever 15

Decoupling gas purification train architecture from electrolysis

Table 7-32: Cost-out Lever 15: Decoupling gas purification train architecture from electrolysis

Calculation Summary
Decoupling the gas purification system allows the scale of the system to be optimised to the overall plant size and configuration, leveraging common equipment to minimise costs. In practice there are limitations to this that cap potential benefits. Worley's analysis indicates that benefits reduce above the 1 GW scale for HP electrolysis. This means that purification packages can feasibly be supplied at the 1 GW scale at a pressure of ~30 barg, with large but acceptable piping (~DN400) and vessels. To achieve a similar scale of purification consolidation for LP electrolysis, hydrogen gas requires compression prior to treatment due to the larger volume. Above this scale, additional compression could help to manage the volume, but this would come at added costs. This analysis applies to all reference projects except for reference project 1, which already has 1 common gas treatment package and cannot gain additional benefits from this lever. The central case saving was determined by replacing the original equipment cost for a with cost data from Worley's database for a large scale (1 GW equivalent) package. This change to the estimate was then subject to the same estimate basis and methodology as the reference estimates.

Cost-Out Lever 16

Medium voltage power gathering system

Table 7-33: Cost-out Lever 16: Medium voltage power gathering system

Title	Description of impact	Theme	Cost-out Context
Medium voltage power gathering system	Power generation and transmission typically operates at voltages in excess of 110 kV (e.g. the reference projects for this study adopt 132 kV and above). A hydrogen production facility transforms this high voltage power down to a medium voltage (33 kV and 11 kV are common medium voltage levels) for reticulation on site to the electrolyser modules, where OEM systems step down voltages further. Cost reductions will arise where it is feasible to change the power gathering system architecture to gather at MV and avoid the need for transformation from high voltage systems and introduce MV switchgear in place of HV equivalents. This opportunity requires a coordinated approach to power system design and hydrogen production facility location.	Systems Integration **Owner** Developers	This lever represents a specific use-case and requires a particular configuration. Developments aligned to this concept are feasible today.

Cost Breakdown												
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)						
Period	**2035**			**2050**		
Probability	-	-	-	-	-	-
Reference project	L	M	H	L	M	H
RP1	-	3%	-	-	3%	-
RP2	-	2%	-	-	2%	-
RP3	-	2%	-	-	2%	-
RP4	-	-	-	-	-	-

Distribution and Modelling	Correlation / relationship to other items
Bernoulli	-

Cost-Out Lever 16

Medium voltage power gathering system

Table 7-34: Cost-out Lever 16: Medium voltage power gathering system

Calculation Summary
This lever represents a specific use-case where sufficient medium voltage power is available in close proximity to the hydrogen production facility. This requires a co-located generator such as behind-the-meter renewables in close proximity. The lever removes the need for high-voltage power supply equipment in this specific scenario. There is a practical limit to the scale to which this is cost-beneficial at around the 1 GW electrolysis equivalent threshold. Above this scale the distances within the renewables area mean medium voltage power systems are not feasible when compared to high voltage alternatives, even if the power source is proximate. As a result, reference project 4 (10 GW) does not stand to benefit from this lever. The central case is applied via the same approach to all reference projects in both 2035 and 2050 – the HV equipment costs in the base power cost block (WB 1100) are removed, and the MV switchyard costs are reduced by a large fraction (around 80%). There are no low and high savings cases for this lever, and it applies only to a small subset of use-cases, between 5 and 10% of projects today, in Worley's experience, are candidates for this approach. This lever provides between 2-3% savings of total reference TIC.

Cost-Out Lever 17

Contracting cost reduction

Table 7-35: Cost-out Lever 17: Contracting cost reduction

Title	Description of impact	Theme	Cost-out Context
Contracting cost reduction	Hydrogen production is a developing market and combines multiple parties in new and novel commercial arrangements. The parties themselves represent differing readiness, experience, risk tolerance and risk awareness. Organisations that participate in the hydrogen production market (e.g. developers, manufacturers, EPC partners etc.) are allocating risk in contract structures and pricing accordingly. As the market matures, capital cost reduction for project development could occur through efficient allocation of risk and established contracting norms. This cost reduction also benefits the cost of finance, project bankability and reduces potential delays; which are all out of the scope for this study. Cost reduction could also arise in the reduction of risk premia applied to the hydrogen production facility by parties involved.	Commercial Choice **Owner** OEMs and Developers	Similar reductions have occurred in adjacent industries as developer, OEM, finance and market norms are established.

Cost Breakdown												
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)							Distribution and Modelling	Correlation / relationship to other items
Period	**2035**			**2050**				
Probability	95%	50%	5%	95%	50%	5%		
Reference project	L	M	H	L	M	H		
RP1	-4%	1%	2%	-2%	2%	5%	Pert	Related to Item 1.
RP2	-2%	2%	5%	-2%	2%	5%		
RP3	-2%	2%	5%	-2%	2%	5%		
RP4	-2%	2%	5%	-2%	2%	5%		

Cost-Out Lever 17

Contracting cost reduction

Table 7-36: Cost-out Lever 17: Contracting cost reduction

Calculation Summary

This lever estimates potential cost reduction from efficient contracting practices and risk allocation. It does this by reducing total contract value, predominantly equipment cost. This affects the total project cost and excludes owners costs. This is applicable to all reference projects in both 2035 and 2050 scenarios.

The reductions are to reflect improved contract norms and efficiency. Worley take analogue from EPC contract models and margins, where they are known.

The risk premium changes applied to the total project cost of each reference project are listed below. These are based on Worley experience and understanding of current risks. Notably, there is a credible scenario of cost increase in this lever. This lever speaks to risk allocation, and there remains a cost upside risk. The low savings case attempts to reflect potential cost overruns on individual projects.

Reference project	Equipment Cost Reduction (2035)			Equipment Cost Reduction (2050)		
	Low Savings	Central	High Savings	Low Savings	Central	High Savings
1	-4%	1%	2%	-2%	2%	5%
2, 3, 4	-2%	2%	5%	-2%	2%	5%

Lower savings are estimated for reference project 1. This is because SOEC technology is not as far long the deployment curve as alternatives, and is perceived to be higher risk. This difference is not expected to be sustained out to 2050.

Cost-Out Lever 18

Purchase lowest cost equipment

Table 7-37: Cost-out Lever 18: Purchase lowest cost equipment

Title	Description of impact	Theme	Cost-out Context
Purchase lowest cost equipment	The reference costs for this study use a statistical representation of real-world equipment prices from Worley's database. The cost data covers a wide range of pricing dependant on location, project and OEM. Capital cost reduction could directly come from a developer's wish to prioritize a lower TIC over other factors (JV, local sourced equipment etc). The changing landscape of OEM providers enables access to different strategic alliances, aligned with modularisation and pre-fabrication. Anecdotally, early cheaper modules struggled to achieve parity in efficiency and/or degradation life against their peers, though this development divide appears to have narrowed. The benefits of a lower TIC focus needs to be done in conjunction with alignment of specifications to Australia-compliant standards and regulations and managing internation supply chains.	Commercial Choice **Owner** Developers	This is a direct cost reduction through a price-led choice by project developers, and lowest cost equipment can be accompanied by other trade-offs.

Cost Breakdown												
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)						
Period	**2035**			**2050**		
Probability	95%	50%	5%	95%	50%	5%
Reference project	L	M	H	L	M	H
RP1	3%	5%	8%	3%	5%	8%
RP2	11%	18%	21%	11%	18%	21%
RP3	11%	14%	16%	11%	14%	16%
RP4	12%	19%	23%	12%	19%	23%

Distribution and Modelling	Correlation / relationship to other items
PertAlt	Negative correlation to Item 1 (-0.7).

Cost-Out Lever 18

Purchase lowest cost equipment

Table 7-38: Cost-out Lever 18: Purchase lowest cost equipment

Calculation Summary

This lever estimates cost reductions achievable through deliberate procurement of lower-priced electrolyser equipment, rather than with a focus on other drivers (local content, partnerships etc) and purchasing at the average or upper end of observed market prices. The effects of this are applicable to all reference projects for 2035 and 2050, but are limited to the electrolyser stacks and electrical equipment. Cost reductions for the gas purification equipment are already accounted for in lever 15 and are excluded in this item.

The electrolyser costs used in the base estimates are derived from Worley's internal database and reflect an average price across the market. As this includes European and other expensive vendors, these costs are relatively higher than the lowest cost electrolysers currently available, which are AWE electrolysers produced in China. The cost reduction for the reference project 3 central case is therefore approximated as the difference between European and Chinese AWE vendor costs based on Worley's past project experience and vendor data. The expectation is that percentage savings for Chinese electrolysers will be highest for technologies with the highest production in China relative to Europe. Since there are an increasing number of vendors producing lower cost PEM electrolysers in China, the same cost reductions are applied to the reference project 2 and 4 central and high savings cases as done in reference project 1. SOEC cost reductions are limited due to minimal hydrogen projects at scale utilising them.

The cost reductions listed below are applied to electrolyser stack and electrical equipment costs only – other costs are fixed. The reductions apply at the time of writing and are expected to remain similar out to 2050, but this may be eroded if the incentivisation of export manufacturing decreases.

Reference project	Equipment Cost Reduction (2035 and 2050)		
	Low Savings	Central	High Savings
1	10%	15%	25%
2, 4	30%	50%	60%
3	40%	50%	60%

Cost-Out Lever 19

Digitalisation and predictive design

Table 7-39: Cost-out Lever 19: Digitalisation and predictive design

Title	Description of impact	Theme	Cost-out Context
Digitalisation, predictive design and advanced scheduling	Hydrogen facilities can adopt advanced digital tools such as predictive modelling, simulation, and real-time monitoring to optimize design and operation. By using data-driven analytics, facilities can accurately forecast performance and risks instead of relying on conservative assumptions. This reduces the need for excessive overdesign margins and contingencies which can lead to higher TIC. A specific example of how digitalisation leads to project surety adopted for this cost study is through Generative scheduling (AI scheduling). Generative scheduling works by building a model of the physical and spatial constraints of how work needs to be done on-site. The tool allows testing of any assumptions and options on installation rates, access, and productivity, producing hundreds of thousands of scenarios. These scenarios are then analytically tested to generate an optimised resource-loaded schedule, and a risk-aware view of dependencies.	Project Delivery **Owner** Developers	Similar cost reductions occur in many analogous industries. These include solar photovoltaic power generators, and heavy industry processes.

Cost Breakdown												
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)						
Period	**2035**			**2050**		
Probability	90%	50%	10%	90%	50%	10%
Reference project	L	M	H	L	M	H
RP1	0.4%	0.7%	1.8%	0.4%	0.7%	1.8%
RP2	0.3%	0.7%	1.7%	0.3%	0.7%	1.7%
RP3	0.3%	0.7%	1.5%	0.3%	0.7%	1.5%
RP4	0.3%	0.7%	1.6%	0.3%	0.7%	1.6%

Distribution and Modelling	Correlation / relationship to other items
Pert	-

Cost-Out Lever 19

Digitalisation and predictive design

Table 7-40: Cost-out Lever 19: Digitalisation and predictive design

Calculation Summary

This lever estimates cost reductions from improved project design certainty and construction scheduling, enabled by digital tools such as predictive modelling, digital twins, and advanced (including AI-assisted) scheduling. In this calculation, benefits of these practices are expressed through reductions in all of the following:

- Contractors' engineering – effective use of digital twins and data-centric engineering to reduce engineering effort
- Construction modelling and scenarios – to maximise tool time and minimize labour force, related to Item 21
- Commissioning – reduce cost and duration by completing some commissioning activities virtually in a low/no risk environment
- Project and construction management – productivity improvement from parallel work fronts in construction and project management cost reduction due to schedule acceleration. This facet is partially offset by higher work intensity (productivity improvements are subject to other cost-out levers).
- Temporary facilities and mobile equipment hire – savings that scale with the schedule duration

The adjustments made to the relevant costs are summarised in the table below. These are applied to all reference projects and WBS items for the 2035 and 2050 scenarios.

Cost type	Cost reduction by WBS and item (2035 and 2050)		
	Low Savings	Central	High Savings
Contractors' engineering allowance	5.0%	10%	20%
Mobile equipment hire duration	1.0%	2.5%	10%
Commissioning allowance	1.3%	2.5%	5%
Project and construction management allowance	0.63%	1.3%	5%
Temporary facilities allowance	-	0.75%	3%

Cost-Out Lever 20

Industrial hub co-location and beneficial use of Common Use Infrastructure

Table 7-41: Cost-out Lever 20: Industrial hub co-location and beneficial use of Common Use Infrastructure

Title	Description of impact	Theme	Cost-out Context
Industrial hub co-location and beneficial use of Common Use Infrastructure	Hydrogen production facilities are typically sited within industrially zoned areas, and the selection of a favourable site includes balancing multiple oftentimes competing, factors. Co-locating industry and the emergence of industrial hubs supporting hydrogen production could create opportunities for synergistic use of common infrastructure. Other aspects of cost reduction could arise in lower costs for utility provision and streamlining development approvals (approvals feature in Item 24).	Project Delivery **Owner** Developers and Policy Makers	A direct example of a benefit will be heat available to SOEC derivative hydrogen production. Other synergies will emerge.

Cost Breakdown													
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage	

Cost Reduction Potential (%)							Distribution and Modelling	Correlation / relationship to other items
Period	**2035**			**2050**				
Probability	99%	50%	20%	99%	50%	20%		
Reference project	L	M	H	L	M	H		
RP1	-	5%	5%	-	5%	5%	Binomial	-
RP2	-	6%	6%	-	6%	6%		
RP3	-	7%	7%	-	7%	7%		
RP4	-	-	-	-	-	-		

Cost-Out Lever 20

Industrial hub co-location and beneficial use of Common Use Infrastructure

Table 7-42: Cost-out Lever 20: Industrial hub co-location and beneficial use of Common Use Infrastructure

Calculation Summary

This lever assesses the potential savings from co-location due to shared common-use infrastructure. This most usually relates to shared utilities (such as water treatment, site preparation, utilities, and high-voltage systems). This lever assesses shared utilities and project development costs as it is most directly within the scope of the reference estimates.
This is a conditional, event-based lever that either occurs and results in a cost reduction (quantified as the central case and high savings case) or does not occur and results in no cost reduction (the low savings case).

The lever is applied using the same approach for 2035 and 2050 to all reference projects except for reference project 4. This is because the scale of reference project 4 means it would likely be the anchor project for common-use infrastructure, rather than a beneficiary; or the demand from this project would simply eclipse any neighbouring synergies. The cost reductions apply to the following WBS items. Cost improvements for reference project 1 are not extended to NPI or Site Prep & Civil costs as it was already expected the ref 1 project would already be a developed industrial site.

Reference project	WBS / cost item	Cost Reduction (2035 and 2050)		
		Low Savings	Central	High Savings
1, 2, 3	Power (removal of HV power reception)	-	100% installed cost reduction	100% installed cost reduction
	Utilities (shared utility systems)	-	50% installed cost reduction	50% installed cost reduction
	Owners Costs (reduced approvals costs)	-	0.5% TIC reduction	0.5% TIC reduction
2, 3	NPI, Site Prep & Civils (reduced costs in an already developed hub)	-	100% installed cost reduction	100% installed cost reduction

The resultant savings range up to 5-7% of the reference TIC, owing primarily to potential reduction of the power infrastructure costs in scope, as well as NPI, site prep and civil costs for reference projects 2 and 3. Note that in practice, if the project's CAPEX contribution drops to zero, the provider of common use infrastructure would likely levy the use of a common utility to recoup their own CAPEX. This would form a significant OPEX charge which will impact the levelised cost of hydrogen but is not in frame for this study.

Cost-Out Lever 21

Lean construction methods

Table 7-43: Cost-out Lever 21: Lean construction methods

Title	Description of impact	Theme	Cost-out Context
Lean construction methods	Labour tool time in Australia is rarely over 30%. Cost reduction will come from bringing global best-practice in planning and execution to Australian projects. Using latest planning and execution methods, tool-time can reach 55-60%. Improvement will involve addressing areas such as: • Improved permit to work processes, • Optimised shift handovers, • Closer crib room / warehouse locations, optimising personnel movement • Materials and tool pre-kitting, and pre-delivering these to the work-site • Schedule optimisation and detailed task planning, including AI scheduling (see Item 20) • Continuous improvement programs addressing things like waste elimination.	Project Delivery **Owner** Developers	This cost item reduces cost through reducing construction labour costs. It does this by improving tool time and increasing the productivity of that time.

Cost Breakdown												
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)						
Period	**2035**			**2050**		
Probability	99%	50%	5%	99%	50%	5%
Reference project	L	M	H	L	M	H
RP1	1%	3%	5%	1%	3%	5%
RP2	1%	3%	6%	1%	3%	6%
RP3	1%	4%	8%	1%	4%	8%
RP4	1%	3%	7%	1%	3%	7%

Distribution and Modelling	Correlation / relationship to other items
Pert	Negative correlation to Item 5 (-0.7).

Cost-Out Lever 21

Lean construction methods

Table 7-44: Cost-out Lever 21: Lean construction methods

Calculation Summary

This lever estimates cost reductions achievable through improved construction labour productivity, driven by adoption of lean construction practices. Labour tool time in Australia is rarely over 30%. This lever estimates cost reduction by improving construction labour productivity factors.

These productivity improvements can apply now and will not change out to 2050. The modified productivity factors are applied as adjustments to the site erection labour and productivity factors for all projects. The nominal factors used and the applicable WBS items that have construction labour allowances are listed in the table below. These are based on Worley's experience and understanding of construction methods.

Reference project	WBS	Base factor	Adjusted factor (2035 and 2050)			
			Low Savings	Central	High Savings	Factor
All	Power systems, BESS	1.00	1.00	0.75	0.50	Fraction site erection
	Compression, utilities	1.00	0.90	0.75	0.50	Productivity adjustment
	WHRU/Steam	1.20	1.10	0.95	0.70	
1, 2, 3	Electrolysis	1.00	0.90	0.75	0.50	Site erection
4	Electrolysis	0.90	0.81	0.68	0.45	

Cost-Out Lever 22

Project-to-project standardisation

Table 7-45: Cost-out Lever 22: Project-to-project standardisation

Title	Description of impact	Theme	Cost-out Context
Project-to-project standardisation	Complex projects are typically developed and optimised for the location, demand and governance requirements. There is a shift toward rapidly deployable systems to reduce cost. These systems borrow ideas from software engineering: modularity, versioning, reuse — and are yielding significant, reproducible, compounding productivity gains. Cost reductions could come from creating eco-systems of Developers/Owners, OEMs, EPC(M)s, Construction contractors and potentially even Regulators executing standardised projects and delivering against a mutually agreed, ambitious improvement curves from project to project. This is enabled by deeper modularisation, which is Item 2 in this list.	Project Delivery **Owner** Developers	This cost item reduces cost through repetition of completed projects, improving the process via learning and experience, reducing the time and cost to implement.

Cost Breakdown													
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)							Distribution and Modelling	Correlation / relationship to other items
Period	2035			2050				
Probability	95%	50%	5%	95%	50%	5%		
Reference project	L	M	H	L	M	H		
RP1	-	-	-	0.3%	3%	7%	Pert	Positive correlation to Item 2 (0.5).
RP2	-	4%	8%	0.4%	4%	9%		
RP3	-	4%	7%	0.4%	4%	8%		
RP4	-	-	-	-	-	-		

Cost-Out Lever 22

Project-to-project standardisation

Table 7-46: Cost-out Lever 22: Project-to-project standardisation

Calculation Summary

In this calculation, the savings achievable through project-to-project standardisation are a combination of stacking the following cost reduction mechanisms:

- A common proponent across a series of projects or development in a common jurisdiction – this reduces owners' costs
- A common vendor – this reduces fabrication hours and increases productivity
- A common EPC contractor – this reduces engineering effort and contingency

These cost reductions are applied to the BESS (1200) and electrolysis (1300) WBS items; the other items are well understood and already benefit from standardisation or are site-specific (e.g. NPI). Reference project 4 is excluded from the analysis as it represents a first-of-a-kind scale that would require changes to current design, supply chain and execution strategies. reference project 1, which uses SOEC technology, is not likely to experience savings from standardisation by 2035 due to its limited deployment and hence is only included in the 2050 case. Savings for BESS are only applied to the larger utility scale reference projects 2 and 3.

The table below summarises the cost reduction methodology adopted.

Year	Ref. Project	WBS	Fabrication shop hours reduction			Contingency allowance reduction			Engineering cost reduction			Owners cost reduction		
			Low Savings	Central	High Savings	Low Savings	Central	High Savings	Low Savings	Central	High Savings	Low Savings	Central	High Savings
2035	2, 3	1200, 1300	-	5%	10%	-	17%	20%	-	5%	10%	-	-	-
2050	1	1300	5%	10%	20%	-	17%	20%	5%	10%	20%	-	-	10%
	2, 3	1200, 1300	5%	10%	20%	-	17%	20%	5%	10%	20%	-	-	10%

Cost-Out Lever 23

Scope minimisation to minimum technical solution (MTS) across all components

Table 7-47: Cost-out Lever 23: Scope minimisation to minimum technical solution (MTS) across all components

Title	Description of impact	Theme	Cost-out Context
Scope minimisation to minimum technical solution (MTS) across all components	Cost reduction could come from project adherence to a minimum technical solution across all components. This requires control of both scope and specification. In general organisations and their projects tend to succeed in control of one factor, it is rare that both are minimised in concert. Value engineering efforts by owners' teams to control scope by engineering contractors can yield double-digit percentage cost improvements. Similarly, challenging the specification of every individual component down to what is required (the Minimum Technical Solution, or specifying to the Technical Limit) will yield significant cost reduction benefits.	Project Delivery **Owner** Developers	By defining and adhering to minimum scope and controlling specifications to minimise design margin and contingency cost can be reduced

Cost Breakdown												
Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)						
Period	**2035**			**2050**		
Probability	99%	50%	5%	99%	50%	5%
Reference project	L	M	H	L	M	H
RP1	-	1%	3%	-	1%	3%
RP2	-	2%	4%	-	2%	4%
RP3	-	1%	3%	-	1%	3%
RP4	-	2%	4%	-	2%	4%

Distribution and Modelling	Correlation / relationship to other items
Pert	Positive correlation to Item 2 and Item 22 (0.5).

Cost-Out Lever 23

Scope minimisation to minimum technical solution (MTS) across all components

Table 7-48: Cost-out Lever 23: Scope minimisation to minimum technical solution (MTS) across all components

Calculation Summary

This calculation methodology estimates cost reduction achievable when considering over-specification and scope additional to the minimum functional need. Cost savings are estimated through two mechanisms:

- Control of scope – using value engineering to minimise scope, quantified as a reduction in equipment item costs
- Control of specifications – simplifying and limiting engineering specifications to what is necessary, quantified as a reduction in engineering costs

These cost reductions apply to all reference projects with the exception that control of specifications is not applicable to reference project 1. SOEC is a less mature technology than AWE or PEM and operates at unique conditions (i.e. very high temperature), so the expectation is there would be less ability to use alternative specifications. The relevant WBS items include the electrolyser modules (1310), gas purification (1330) and hydrogen compression (1400), though the latter two are only impacted by specification control and not scope control. This is because gas purification and hydrogen compression equipment are already supplied as standard packages with minimal added scope.

The cost reduction scenarios are listed in the table below. The same reductions are applied in both 2035 and 2050.

Reference project	WBS	Cost saving mechanism	WBS Cost reduction (2035 and 2050)		
			Low Savings	Central	High Savings
All	Electrolyser modules	Control of scope	-	2.5% equipment item cost reduction	5% equipment item cost reduction
2, 3, 4	Electrolyser modules, gas purification, compression	Control of specification	-	5% engineering cost reduction	12.5% engineering cost reduction

Cost-Out Lever 24

Streamlining of development approvals

Table 7-49: Cost-out Lever 24: Streamlining of development approvals

Title	Description of impact	Theme	Cost-out Context
Streamlining of development approvals	The process of gaining the necessary project approvals are a common contributor to project revision, delay or cancellation to. Improved collaboration and alignment will remove or reduce this cost and risk, much of which is incurred prior to financial commitment. The collaboration and alignment that will reduce cost is expected to address the root causes for long delays such as: • Poor alignment between societal objectives and regulatory approval processes: e.g. Delaying environmental or planning approvals for mission-critical transmission projects impacting energy transition • Lack of performance objectives for or compliance from regulatory authorities providing approvals • Lack of coordination, collaboration and problem solving between agencies, applicants and peak bodies. This is a complex set of problems and the solutions creating cost reduction and surety could include: • Policy incentives for lower capital cost (or total cost of ownership) developments • Priority approvals for standardised designs • Inclusion of policy makers and regulators in eco-systems delivering standardised lowest cost infrastructure • Lead agency appointment for approval of specific types of infrastructure • Published performance against approval KPIs.	Project Delivery **Owner** Policy Makers	This cost item improves collaboration and alignment on necessary approvals, reducing the required time and opportunities for revision, delay or cancellation of projects.

Cost Breakdown

Power Systems	*Electrolyser Stacks*	*Electrical Equipment*	*Purification and treatment*	Compression	Steam Generation	Utilities	NPI and connections	Common Indirects	EPC Management	Owners' costs	Storage Compression	Storage

Cost Reduction Potential (%)

Period	2035			2050		
Probability	99%	50%	5%	99%	50%	5%
Reference project	L	M	H	L	M	H
RP1	-	-	-	-	-	-
RP2	-	0.3%	1.0%	-	0.3%	1.0%
RP3	-	0.3%	1.0%	-	0.3%	1.0%
RP4	-	0.3%	1.0%	-	0.3%	1.0%

Distribution and Modelling	Correlation / relationship to other items
Pert	Positive correlation to Item 2 and Item 22 (0.5).

Cost-Out Lever 24

Streamlining of development approvals

Table 7-50: Cost-out Lever 24: Streamlining of development approvals

Calculation Summary

This lever estimates the possible cost reduction from improving the efficiency, coordination, and predictability of development and regulatory approval processes. The methodology assumes that approval streamlining primarily affects owners costs.

This lever is applicable to all reference projects except for reference project 1. This project is assumed to be adjacent to a brownfield facility supplying waste heat and therefore the expectation is it would enjoy a straightforward approvals pathway. Consistent methodology is used for the 2035 and 2050 scenarios.

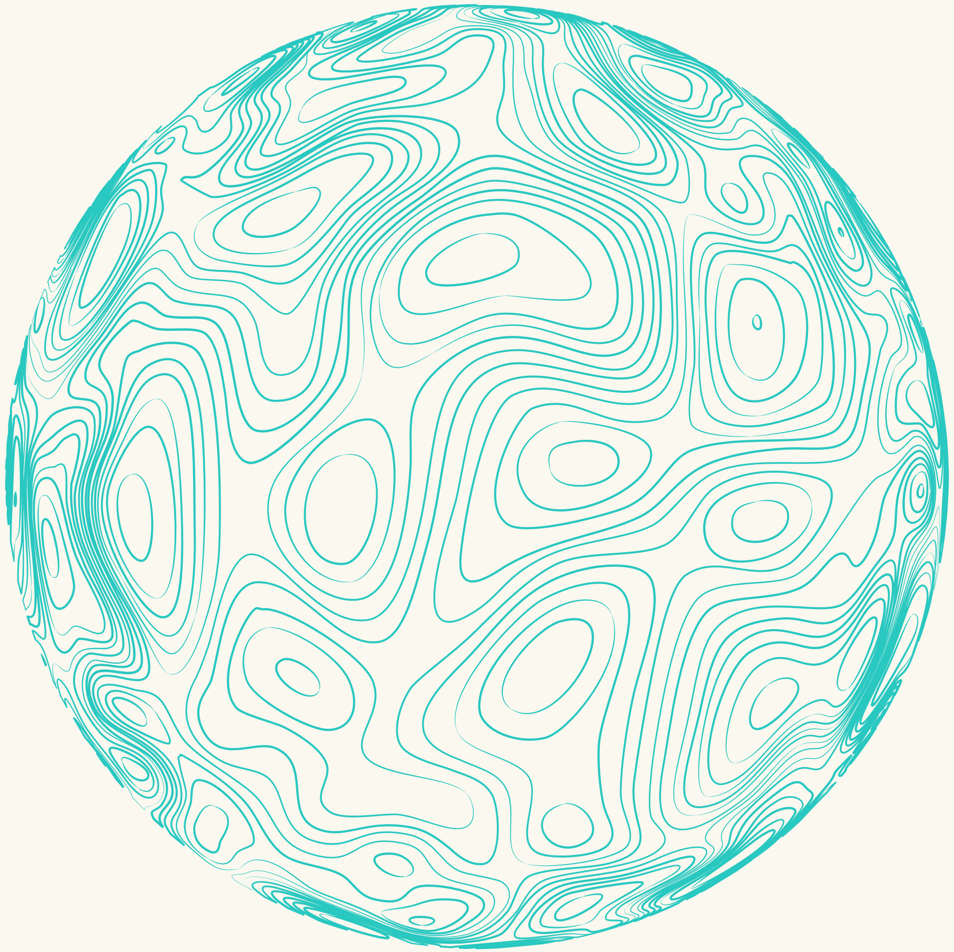
The owners cost reductions for each scenario are provided in the table below. These reductions are underpinned by the following assumptions based on Worley's experience:

- Project execution after FID takes up to 6 years to completion
- Streamlined approvals could reduce execution duration by between 0.5 – 1.5 years, and reduce engineering re-work prior to financial close
- Worley also have regard for the fact that technology OEMs and Licensors carry a risk premium for Australian projects. This is estimated by another allowance reduced from the reference owners' cost. Note that this cost reduction, in practice, would be reflected in equipment direct costs passed through to developers.

Reference project	Owners cost allowance reduction (2035 and 2050)		
	Low Savings	Central	High Savings
2, 3, 4	-	7%	21%

8.0

Hydrogen Storage Modelling



Storage

Three hydrogen storage technologies form the basis for three comparable cost estimates

A portion of hydrogen production facilities operate electrolysis dynamically, typically in response to fluctuating electricity prices or availability. To reduce the impact of this dynamic on downstream users, some facilities incorporate gaseous hydrogen storage to buffer production.

Adding H2 storage and compression requires capital investment in extra equipment, which increases TIC but helps lower the total cost of ownership by reducing operating expenses, mainly electricity costs.

This study provides three reference estimates for storage technologies at reference project 2. Cost reductions for these storage estimates are projected for 2035 and 2050 and are prepared on the same basis as all other estimates in this report. This chapter includes:

- The basis and outcomes of the storage reference estimates.
- A list of Cost-out levers that apply to storage technologies.
- Results from the probabilistic application of these levers to the estimates.

8.1 Basis

The following hydrogen storage technologies with associated compression are based on reference project 2 (1 GW of PEM in SA). All estimates follow the same basis as others in this study report:

1. Medium Pressure (MP) Storage Vessels – Welded steel vessels.
2. High pressure (HP) Storage Vessels – Type 1 steel multi-element gas containers (MEGCs).
3. Pipeline Storage.

The volume of storage required for a specific application is typically the subject of time-dynamic optimisation. For this study Worley has developed a basis that reflects a representative storage application:

- The quantity of storage is based on support for 16 hours of hydrogen production at electrolyser nameplate rates. This nomination is appropriate for a hybrid solar and wind electricity supply, for a downstream offtaker with relatively constant demand (e.g. for use in direct-reduced iron production)
- Two-thirds of the hydrogen produced is routed to storage, through storage compression. The remainder is a constant supply through product compression.
- All storage compression is direct-air cooled multi-stage reciprocating units.

Specific storage technology metrics and capacities are provided in Table 8-1.

Table 8-1: Storage technology metrics and capacities

Parameter	Units	MP Vessels	HP Vessels	Pipeline
Storage capacity	t	290	290	290
Storage pressure	barg	30 – 80	30 – 330	30 – 80
Storage size	-	4.5 x 36 m vessels (ID x t/t L)	12.2 x 2.4 x 1.4 m skids (L x W x H)	DN 1050 104 km
Number of units	#	137 vessels	920 skids	1
Material	-	Carbon steel	Carbon steel	Carbon steel
Compressor duty	MW	5.5	14	5.5

Storage Reference Estimates

Hydrogen storage technologies increase reference project 2's TIC by 16-32%.

8.2 Storage technology estimates

The storage estimates were developed on the same basis as the reference project estimates (in Chapter 5). A summary of the storage estimates is given in Table 8-2, and overview in Figure 8-1. The addition of the storage component increases the reference project 2 estimate of 5,274 AUD/kWe by between 16 and 32% across technology options.

Table 8-2: Summary of storage cost estimates

Direct Costs (AUDm)	**Technology 1:** MP Storage Vessels	**Technology 2:** HP Storage Vessels	**Technology 3:** Pipeline Storage
Hydrogen Storage	464	561	1,047
Storage	*433*	*498*	*1,016*
Storage Compression	*31*	*63*	*31*
Indirect Costs (AUDm)			
Common Indirects	258	300	468
Engineering and PM	64	75	107
Owners' costs	37	45	75
Total H2 Storage Cost (AUDm)	**823**	**980**	**1,697**
Storage total AUD/kWe (reference project 2)	823	980	1,697
Storage total AUDm/t	2.84	3.38	5.85
Combined TIC AUD/kWe (reference project 2)	**6,098**	**6,225**	**6,971**
Change to reference project 2 TIC (+%)	+16%	+19%	+32%

Storage Reference Estimates

Three hydrogen storage technologies form the basis for three comparable cost estimates

Figure 8-1 presents the storage estimates on an AUD/kWe basis, noting that reference project 2 is a 1,000 MWe facility. Estimates are also shown in AUDm/t basis. Storage comprises 88-97% of the total cost for each technology option. The top three cost items across each technology's storage component is procurement (21-44%), installation and construction (10-40%), and contingency (20-21%).

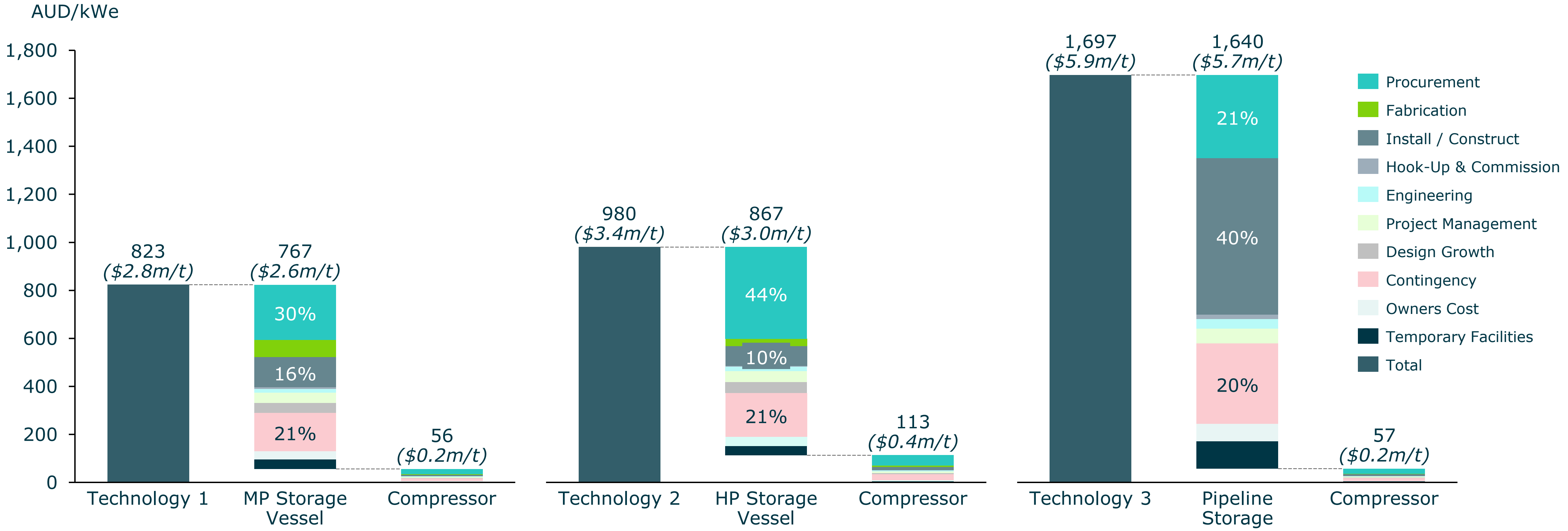


Figure 8-1: Storage cost estimate breakdowns

Storage

Relevant Cost-out levers are identified and applied to Hydrogen storage

8.3 Storage modelling summary

The Cost-out Levers relevant to hydrogen storage and compression were identified. They are listed below in Table 8-3. Refer to Chapter 7 for details.

Table 8-3: List of cost-out levers relevant to Hydrogen storage

Item	Title
1	Development maturity and collective industry learning
5	Advanced construction methods reducing field hours
14	Material substitution in piping, vessels and other equipment
17	Contracting cost reduction
19	Digitalisation, predictive design and advanced scheduling
21	Lean construction methods
23	Scope minimisation to minimum technical solution (MTS) across all components
24	Streamlining of development approvals

Note:

1. Modular MP and HP hydrogen storage solutions are already the basis for the reference estimates for storage, and that concept does not appear on this list as a result.

These levers were calculated independently, and the estimated cost reductions were modelled in a Monte Carlo model. This Monte Carlo model adopted the same steps as described in Chapter 4, refer to Figure 4-2 for details.

When compared to the broader hydrogen production facility cost assessment, there are generally fewer saving opportunities identified for storage. This is predominantly because the core technologies for storage are substantially more established than hydrogen production core technologies.

The levers identified are those that reduce risk specific to application in hydrogen storage, and levers that explore excellence in project delivery.

The results of the modelling are presented on the following pages.

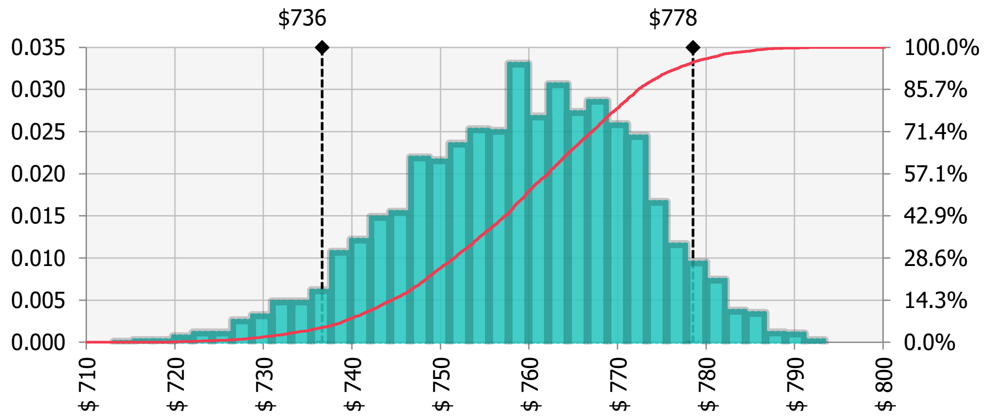
Storage cost reductions to 2035

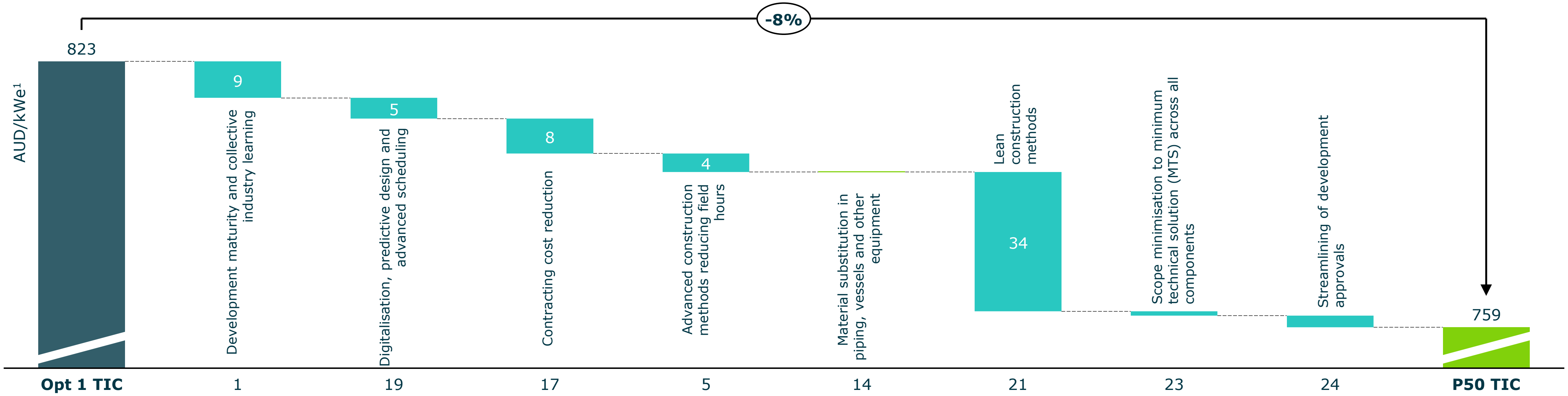
Storage Modelling Summary

Option 1, 2035 model results; MP storage vessels for reference project 2, 1,000 MWe PEM in South Australia

Technology option 1, 2035

- Predicted cost reductions in 2035 result in a range between 49 and 82 AUD/kWe.
- The mean cost reduction is 65 AUD/kWe, which is an 8% reduction from today's reference estimate of 823 AUD/kWe.





1. Where values are given in AUD/kWe, these are based on the scale of reference project 2, 1000 MWe.

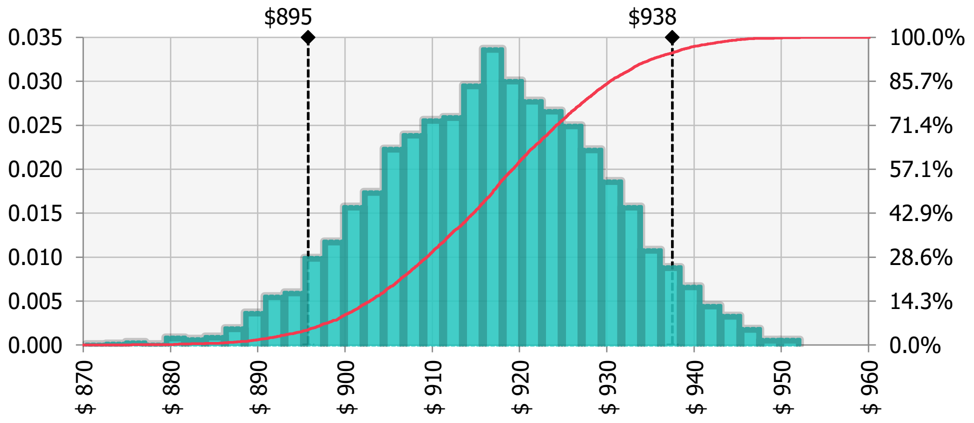
Figure 8-2: Option 1, 2035 summary information

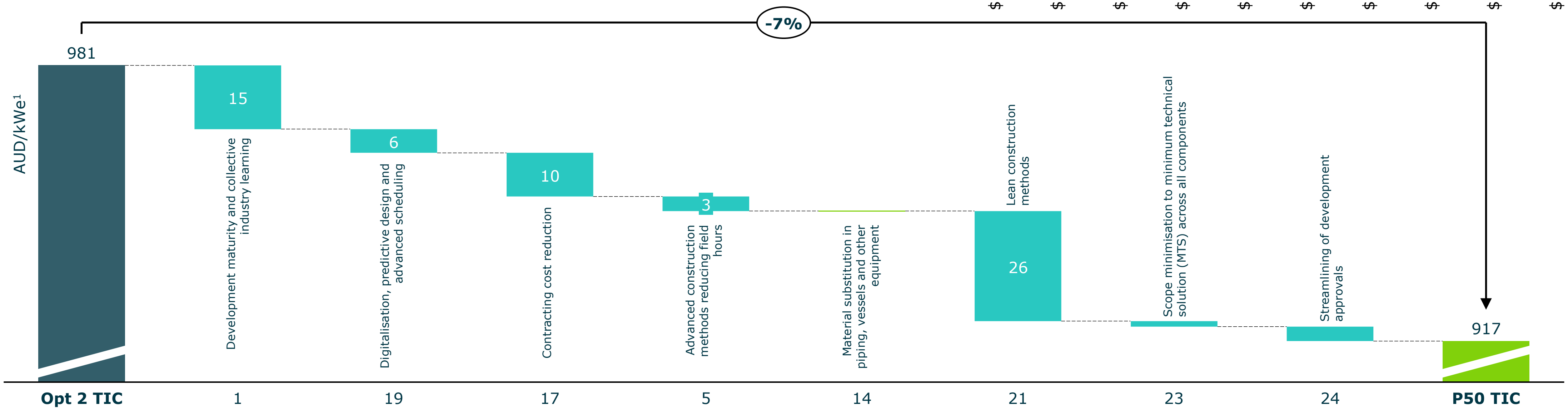
Storage Modelling Summary

Option 2, 2035 model results; HP storage vessels for reference project 2, 1,000 MWe PEM in South Australia

Technology option 2, 2035

- Predicted cost reductions in 2035 result in a range between 48 and 81 AUD/kWe.
- The mean cost reduction is 64 AUD/kWe, which is a 7% reduction from today's reference estimate of 981 AUD/kWe.





1. Where values are given in AUD/kWe, these are based on the scale of reference project 2, 1000 MWe.

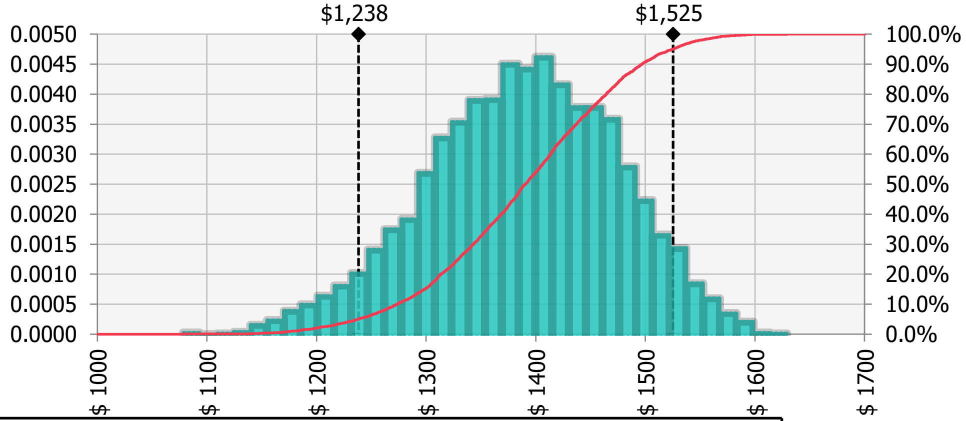
Figure 8-3: Option 2, 2035 summary information

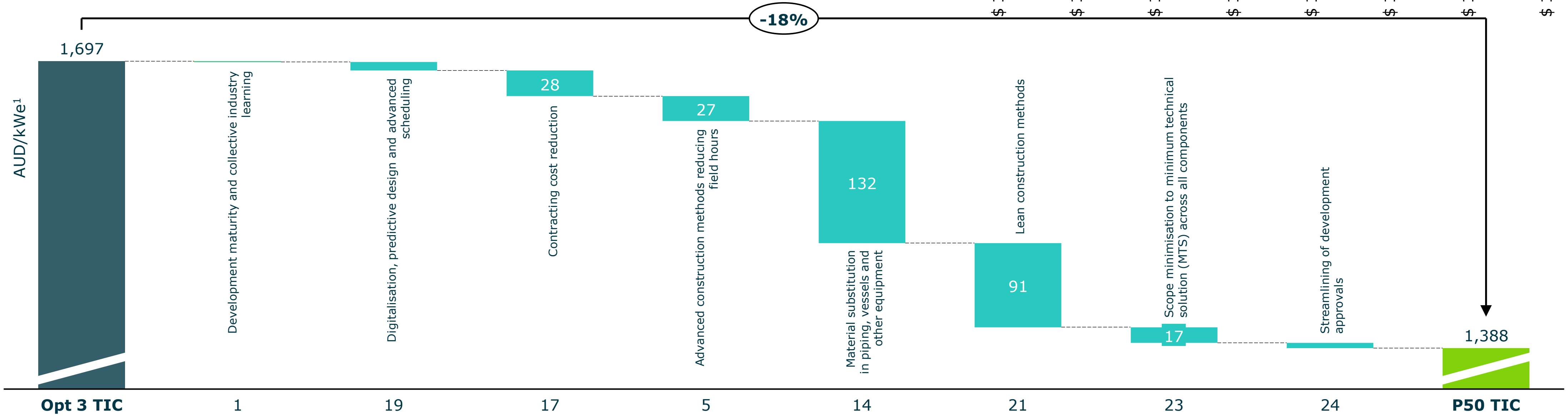
Storage Modelling Summary

Option 3, 2035 model results; Pipeline storage for reference project 2, 1,000 MWe PEM in South Australia

Technology option 3, 2035

- Predicted cost reductions in 2035 result in a range between 200 and 424 AUD/kWe.
- The mean cost reduction is 310 AUD/kWe, which represents an 18% reduction from today's reference estimate of 1,697 AUD/kWe.
- Most of the cost reduction comes from material advancements, or substitution. Carbon steel pipelines in hydrogen service are nascent, and expectations are that cheaper alternatives could reduce cost by up to 9% in 2035.





1. Where values are given in AUD/kWe, these are based on the scale of reference project 2, 1000 MWe.

Figure 8-4: Option 3, 2035 summary information

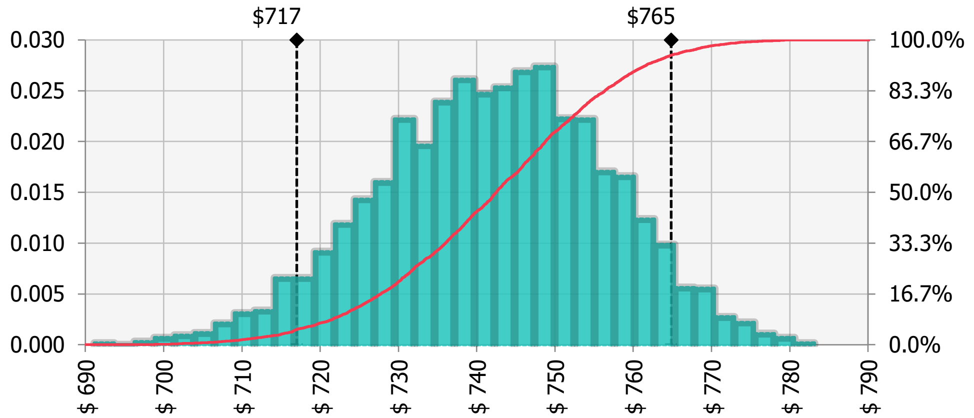
Storage cost reductions to 2050

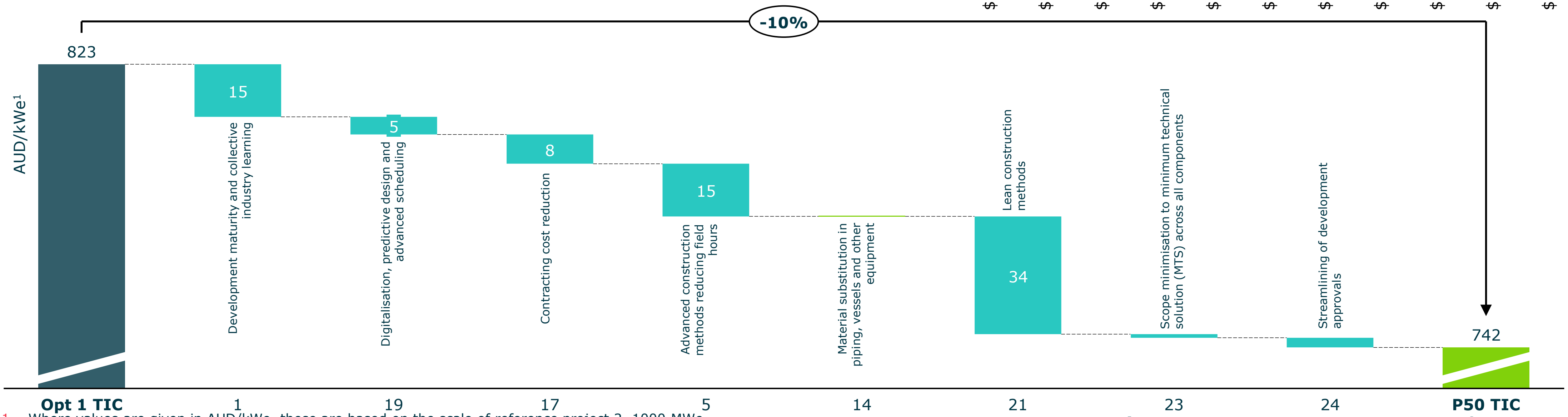
Storage Modelling Summary

Option 1, 2050 model results; MP storage vessels for reference project 2, 1,000 MWe PEM in South Australia

Technology option 1, 2050

- Predicted cost reductions in 2050 result in a range between 63 and 100 AUD/kWe.
- The mean cost reduction is 81 AUD/kWe, which is a 10% reduction from today's reference estimate of 823 AUD/kWe.





1. Where values are given in AUD/kWe, these are based on the scale of reference project 2, 1000 MWe.

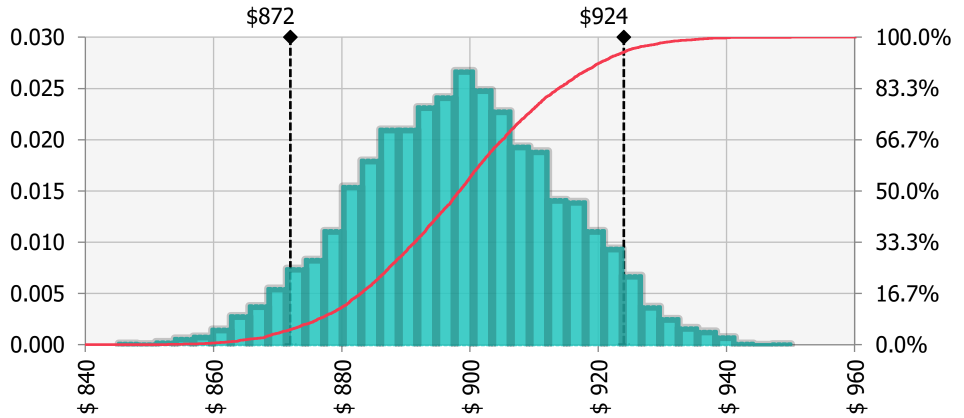
Figure 8-5: Option 1, 2050 summary information

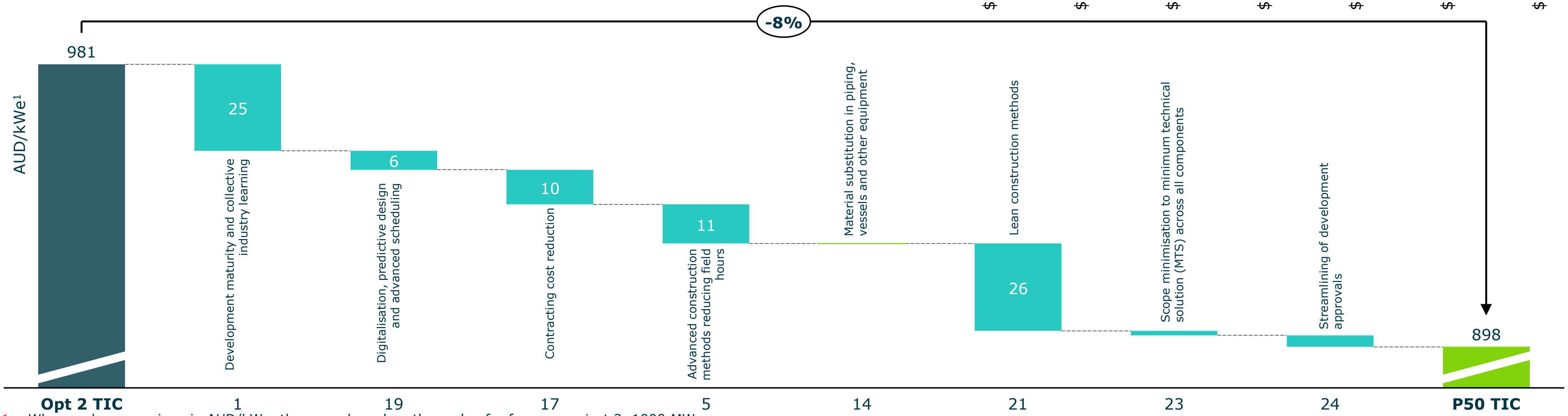
Storage Modelling Summary

Option 2, 2050 model results; HP storage vessels for reference project 2, 1,000 MWe PEM in South Australia

Technology option 2, 2050

- Predicted cost reductions in 2050 result in a range between 62 and 103 AUD/kWe.
- The mean cost reduction is 83 AUD/kWe, which is an 8% reduction from today's reference estimate of 981 AUD/kWe.





1. Where values are given in AUD/kWe, these are based on the scale of reference project 2, 1000 MWe.

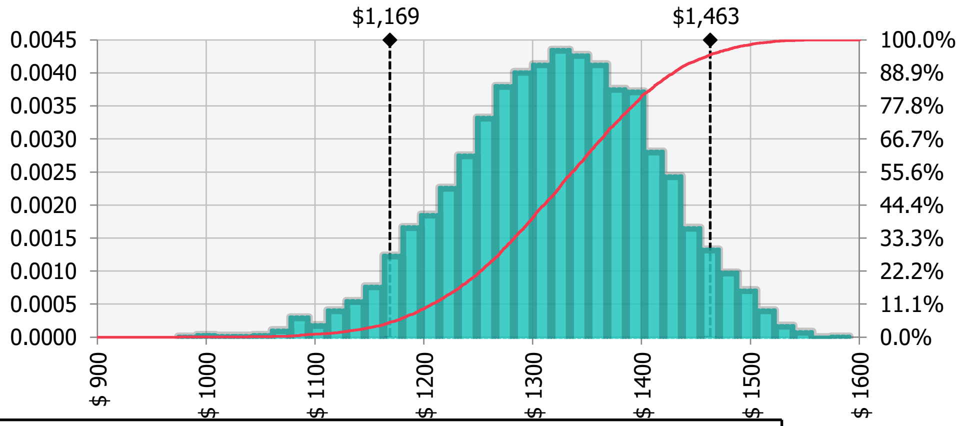
Figure 8-6: Option 2, 2050 summary information

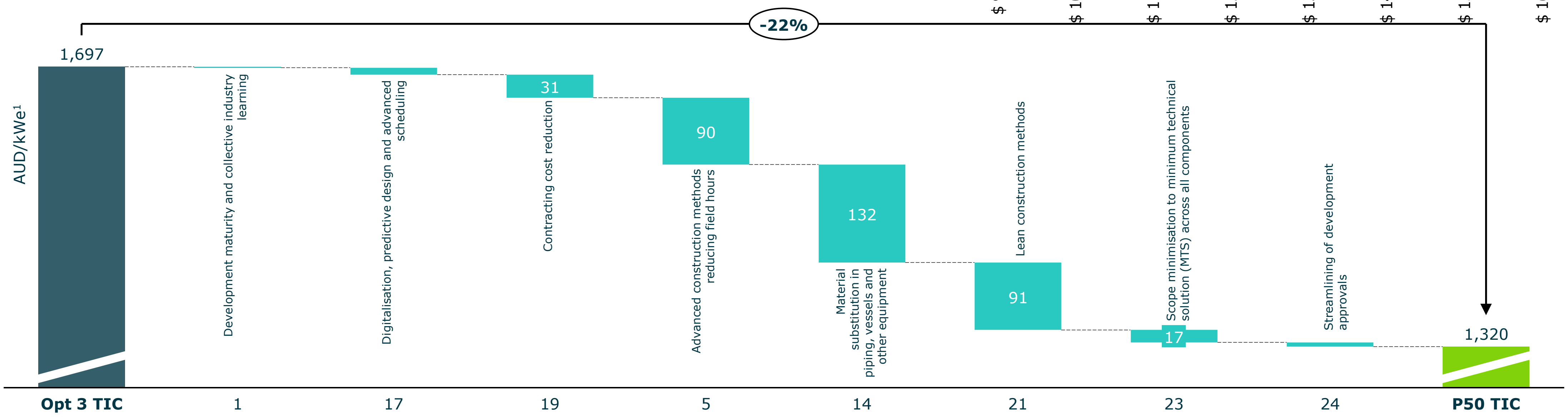
Storage Modelling Summary

Option 3, 2050 model results; Pipeline storage for reference project 2, 1,000 MWe PEM in South Australia

Technology option 3, 2050

- Predicted cost reductions in 2050 result in a range between 264 and 495 AUD/kWe.
- The mean cost reduction is 377 AUD/kWe, which is a 22% reduction from today's reference estimate of 1,697 AUD/kWe.





1. Where values are given in AUD/kWe, these are based on the scale of reference project 2, 1000 MWe.

Figure 8-7: Option 7, 2050 summary information

Acknowledgements

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All errors and omissions are those of the authors.

A

Appendix A

Acronyms and abbreviations

Acronyms and abbreviations

Abbreviation	Definition
A/cm^2	Amperes per square centimetre
AACEI	Association for the Advancement of Cost Engineering International
AI	Artificial Intelligence
ARENA	Australian Renewable Energy Agency
AUD	Australian Dollars
AUDm	Million Australian Dollars
AWE	Alkaline Water Electrolysis
BESS	Battery Energy Storage System
BP	Bipolar Plate
BNEF	BloombergNEF
BOP	Balance of Plant
BTM	Behind the Meter
CFE	Capillary Fed Electrolysis
CI	Confidence Interval
EPC	Engineering, Procurement and Construction
EPCM	Engineering, Procurement and Construction Management
FOAK	First of a Kind
FY	Financial year
g	Grams
GJ	Gigajoule
GL	Gigalitre
GW	Gigawatts

Abbreviation	Definition
GWe	Gigawatts electrolysis installed
HPV	Hydrogen Production Facility
HV	High Voltage
IEA	International Energy Agency
IGBT	Insulated Gate Bipolar Transistors
IRENA	International Renewable Energy Agency
KPI	Key Performance Indicator
kW	Kilowatts
kWe	Kilowatts electrolysis installed
LHV	Lower Heating Value
LV	Low Voltage
MEGC	Multi-Element Gas Container
MP	Medium Pressure
MTS	Minimum Technical Solution
MV	Medium Voltage
MW	Megawatts
MWe	Megawatts electrolysis installed
NOAK	N^{th} of a Kind
NPI	Non-process infrastructure
OEM	Original Equipment Manufacturers
p10	10% probability

Acronyms and abbreviations

Abbreviation	Definition
	50% probability
p90	90% probability
PEM	Proton Exchange Membrane
PTL	Porous Transport Layer
PM	Project Management
RP	Reference Project
SA	South Australia
SOEC	Solid Oxide Electrolyser Cell
t	Tonnes
TIC	Total Installed Cost
VIC	Victoria
WA	Western Australia
WHRU	Waste Heat Recovery Unit

B

Appendix B

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2	ARENA & Hysata	2023	Hysata Capillary-fed Electrolyser Commercial-Scale Demonstration Project	https://arena.gov.au/assets/2024/06/Hysata-High-temperature-ultra-high-efficiency-capillary-fed-electrolysis-project-Poster.pdf
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