

Appendix D: Technology Readiness Grading Methodology

Following the initial Technology Applicability screening, CHE-technology combinations with a score of 1 or higher were further evaluated for technology readiness and assigned one of the *Technology Readiness Grades* described in Table D-1.

Table D-1: Technology Readiness Grade Descriptions

Technology Readiness Grade	Description
Development	• Early product development to pre-production • CHE-technology combination in testing for CHE in controlled experiments
Demonstration	• Early/limited commercial availability • Not fully demonstrated in all environments or not reliable in desired environment
Limited	• Commercially available • Manageable lead times • Possible delays with original equipment manufacturer (OEM) support and replacement parts • Possible time zone delays with technical support • May still experience minor reliability issues • Likely first-generation equipment
Equivalence	• Full commercial availability • Duty cycle equivalence to current CHE diesel counterpart • Lead times similar to diesel • OEM repair support comparable to diesel • Reliable, with up-times comparable to diesel • Achieves operational equivalency with careful practice • Likely 2nd, 3rd, or later generation equipment

Staff evaluated technology readiness using a scoring system with two criteria:

1. Commercial Availability – Up to 500 points, depending on commercial availability or how far it is in the product development cycle. Additional points given for U.S. commercial availability and lead times and part availability equivalent to diesel CHE. Table D-2 outlines the scoring criteria for Commercial Availability.

Operational Feasibility – Up to 500 points, depending on endurance, performance, reliability, and logistics equivalent to diesel CHE.

2. Table D-3 outlines the scoring criteria for Operational Feasibility.

Staff used weighted scores for Commercial Availability and Operational Feasibility, so the most significant contributors carry a higher value. For example, while there are five questions associated with Commercial Availability, a CHE-technology combination that is commercially available achieves a score of 300 out of 500, or 60% of the total potential points.

Table D-2: Scoring Criteria for Commercial Availability

#	Criteria	Assessment	Potential Score
1	Is the CHE commercially available?	Yes	300
		No	0
2	Is the CHE commercially available in the US?	Yes	100
		No	0
3	If the CHE is not commercially available, what is the technology readiness level (TRL1-TRL9)?	TRL 9	250
		TRL 8	200
		TRL 6-7	100
		TRL 4-5	50
		TRL </= 3	0
4	Are the lead times for new CHE purchases comparable to diesel equivalents? • Small Equipment (e.g., Forklift, Yard Tractor, T/S Picks, Truck) < 6 months ¹ • Large Equipment (e.g., Large Crane, Log Stacker, RMG, RTG) < 6 months to 1 year ² • Custom Equipment (e.g., STS Crane, Mobile Harbor Crane) 6 months to more than 1 year ³	Yes	50
		No/Unknown	0
5	Are replacement parts readily available? Equivalent to diesel (</= 2 weeks)	Yes	50
		No/Unknown	0
Total Potential Commercial Availability Points			500

¹ Staff survey of dealers, distributors, and web search.

² Ibid.

³ Ibid.

Table D-3: Scoring Criteria for Operational Feasibility

#	Criteria	Assessment (Container CHE and Heavy Lift Forklifts)	Assessment (Non-container CHE)	Potential Score
1	ENDURANCE: Can the CHE meet the expected operational runtime?	2 shifts (16 hours) w/o charge/refuel	1 shift (8 hours) w/o charge/refuel	150
		2 shifts with charge/refuel between shifts	1 shift with opportunity charging or refueling during shift	125
		1 shift (8 hours)	1 shift (8 hours)	100
		<1 shift or unknown	<1 shift or unknown	0
2	PERFORMANCE: Can the CHE perform on par with diesel baseline (power, torque, speed, etc.)?	Yes		150
		Yes, but with caveats (see reports)		100
		No, or unknown		0
3	RELIABILITY: Is the CHE reliable (similar up/down-time to diesel)?	Yes		150
		Yes, but with caveats (see reports)		100
		No, or unknown		0
4	LOGISTICS: Can the CHE be filled/charged such that operation isn't significantly impacted relative to diesel baseline (Fueling/charging can be accommodated within typical work breaks, lunches, other downtime)?	Yes		50
		No, or unknown		0
Total Potential Operational Feasibility Points				500

Commercial availability means that the CHE is offered to the public by an OEM either on their website or through a dealer or distributor. Staff assigned a score of 300 for commercially available equipment and an additional 100 points if the equipment is available in the U.S. These extra points are assigned due to the additional lead times required to modify the equipment or the associated infrastructure for non-U.S. power systems or additional certifications required for operation in the U.S. See Appendix B for a list of commercially available zero-emission CHE. Equipment that is pre-commercial can be found in Appendix E.

Equipment that is pre-commercial (TRL 9) will take longer to acquire due to undeveloped supply chains for new parts, additional permits, or regulatory approvals required to sell the equipment on the open market. Therefore, this equipment achieves a score of 250.

Equipment in earlier development phases score lower. Additional points are given for lead times and replacement part availability comparable to diesel equipment.

The various tests for the Endurance criteria for container CHE and non-container CHE are due to the differences in operations at container terminals at seaports. Container terminals at seaports often operate at least two shifts per day. While this two-shift requirement may not be the case for all CHE at all container facilities, staff observed this while visiting several seaports. One terminal operator at the Port of Long Beach indicated that if a demonstration yard truck could not operate for two shifts on a single charge, the demonstration “would be considered a failure right from the very start of the project.”⁴ If container CHE cannot endure for two full shifts with one opportunity charge or refuel between shifts, additional CHE may be required to complete the shift at some facilities. This could require additional capital investment. Thus, the low score of 50 for container CHE that are unable to meet the two-shift criteria. Likewise, to achieve a score greater than 0, non-container CHE must be able to complete a full shift with, or without opportunity charging to avoid the potential need for backup CHE to complete the shift. One potential advantage that hydrogen fuel cell CHE has over battery-electric CHE is the ability to fuel the CHE in similar timeframes to diesel, more quickly than it takes to recharge batteries. Therefore, refueling fuel cell CHE may be more feasible for facilities than recharging batteries between shifts. More fuel cell CHE demonstrations are necessary to make this determination.

Scoring for Performance, Reliability, and Logistics is based on discussions between staff and facility operators at California seaports and intermodal railyards in 2024, interviews with CHE OEMs, as well as research of the demonstration, pilot, product launch, and prototype projects listed in Appendix E.

The combined score, with a potential maximum of 1,000 points, determined the Technology Readiness Grade according to Table D-4, which also includes a deployment assessment indicating how ready the equipment-technology combination is for full deployment.

Table D-4: Technology Readiness Grades based on Technology Readiness Scores

Technology Readiness Score	Technology Readiness Grade	Deployment Assessment
0-200	Development	The CHE-technology combination is still in the development phase and is not ready for deployment.

⁴ Southern California Edison, “Final Evaluation report: California Transportation Electrification Priority Review Projects,” April 22, 2021. <https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/sb-350-te/california-te-prp-final-evaluation-report-presentation.pdf>. Staff received similar feedback from other seaport terminal operators.

Technology Readiness Score	Technology Readiness Grade	Deployment Assessment
201-700	Demonstration	Further demonstrations are required to prove the technology before broad deployment. Development teams should closely supervise and manage these demonstrations. The CHE-technology combination is not ready for full deployment.
701-900	Limited	CHE can be deployed on a limited basis. Owner/operators can use this technology with careful supervision and management. Enforceable customer service agreements with OEMs and equipment vendors are crucial for successful deployment.
901-1000	Equivalence	The technology for this CHE type meets functional and operational equivalency to fossil-fuel powered CHE or has replaced fossil fuel equipment completely, becoming the industry standard. Ready for full-scale adoption at most facilities.

Commercial Availability Scoring

Table D-5 through Table D-7 show the Commercial Availability scoring for battery-electric CHE. Table D-8 and Table D-9 show the Commercial Availability scoring for grid-electric CHE. Table D-10 through Table D-12 show the Commercial Availability scoring for hydrogen fuel cell CHE.

Table D-5: Commercial Availability Scoring for Battery-Electric Bulk Material CHE

Equipment Type	Commercially Available Score	Commercially Available in the U.S. Score	TRL Score	Lead Times Score	Replacement Parts Score	Combined Score
Crane, Material Handling	300	100	N/A	0	0	400
Crane, Mobile	300	100	N/A	0	0	400
Crane, Off-Road	300	100	N/A	0	0	400
Dozer	300	0	N/A	0	0	300
Excavator	300	100	N/A	0	0	400
Forklift, Heavy Lift	300	100	N/A	0	0	400
Forklift, Telehandler	300	100	N/A	0	0	400
Haul Truck	300	100	N/A	0	0	400
Loader or Loader-Excavator	300	100	N/A	0	0	400
Log Stacker	0	0	0 ⁵	0	0	0

⁵ No evidence of development.

Table D-6: Commercial Availability Scoring for Battery-Electric Container CHE

Equipment Type	Commercially Available Score	Commercially Available in the U.S. Score	TRL Score	Lead Times Score	Replacement Parts Score	Combined Score
AGV	300	100	N/A	0	50	450
Rail-Mounted Gantry Crane	0	0	0 ⁶	0	0	0
Reach Stacker	300	100	N/A	0	0	400
Rubber-Tired Gantry Crane	300	100	N/A	0	0	400
Shuttle and Straddle Carriers	300	100	N/A	0	0	400
Side Handler	300	100	N/A	0	0	400
Top Handler	300	100	N/A	0	0	400
Yard Truck	300	100	N/A	0	50	450

Table D-7: Commercial Availability Scoring for Battery-Electric Facility Support CHE

Equipment Type	Commercially Available Score	Commercially Available in the U.S. Score	TRL Score	Lead Times Score	Replacement Parts Score	Combined Score
Aerial Lift	300	100	N/A	0	0	400
Cone Vehicle	300	100	N/A	0	0	400
Railcar Mover	300	100	N/A	0	0	400
Utility Truck, Other	300	100	N/A	0	0	400
Utility Truck, Sweeper	300	100	N/A	0	0	400

⁶ No evidence of development.

Table D-8: Commercial Availability Scoring for Grid-Electric Bulk Material CHE

Equipment Type	Commercially Available Score	Commercially Available in the U.S. Score	TRL Score	Lead Times Score	Replacement Parts Score	Combined Score
Crane, Material Handling	300	100	N/A	0	0	400
Crane, Mobile Harbor	300	100	N/A	0	0	400
Crane, Off-Road	300	100	N/A	0	0	400
Excavator	300	100	N/A	0	0	400

Table D-9: Commercial Availability Scoring for Grid-Electric Container CHE

Equipment Type	Commercially Available Score	Commercially Available in the U.S. Score	TRL Score	Lead Times Score	Replacement Parts Score	Combined Score
Rail-Mounted Gantry Crane	300	100	N/A	50	50	500
Rubber-Tired Gantry Crane	300	100	N/A	0	0	400
Ship-to-Shore Crane	300	100	N/A	50	50	500
Yard Truck	0	0	0 ⁷	0	0	0

⁷ Two announcements were made for future demonstrations, but there is no evidence of development. See "International Transportation Service Partners with Elonroad on Zero Emissions at the Port of Long Beach," My New Desk, December 17, 2024. Accessed April 10, 2025. <https://www.mynewsdesk.com/se/elonroad/pressreleases/international-transportation-service-partners-with-elonroad-on-zero-emissions-at-the-port-of-long-beach-3360603> and John Hills, "Kalmar and Elonroad trial Potential Dynamic Charging Breakthrough for Heavy Electric Vehicles," Electric Drives, November 28, 2024. Accessed January 3, 2025. <https://electricdrives.tv/kalmar-and-elonroad-trial-potential-dynamic-charging-breakthrough-for-heavy-electric-vehicles/>.

Table D-10: Commercial Availability Scoring for Hydrogen Fuel Cell Bulk Material CHE

Equipment Type	Commercially Available Score	Commercially Available in the U.S. Score	TRL Score	Lead Times Score	Replacement Parts Score	Combined Score
Crane, Material Handling	0	0	0 ⁸	0	0	0
Crane, Mobile	0	0	0 ⁹	0	0	0
Crane, Mobile Harbor	0	0	100 (TRL6)	0	0	100
Crane, Off-Road	0	0	200 (TRL8)	0	0	200
Dozer	0	0	0 ¹⁰	0	0	0
Excavator	0	0	200 (TRL8)	0	0	200
Forklift, Heavy Lift	300	100	N/A	0	0	400
Forklift, Telehandler	0	0	100 (TRL7)	0	0	100
Haul Truck	0	0	100 (TRL7)	0	0	100
Loader or Loader-Excavator	0	0	200 (TRL8)	0	0	200
Log Stacker	0	0	0 ¹¹	0	0	0

⁸ No evidence of development.

⁹ No evidence of development.

¹⁰ No evidence of development.

¹¹ No evidence of development.

Table D-11: Commercial Availability Scoring for Hydrogen Fuel Cell Container CHE

Equipment Type	Commercially Available Score	Commercially Available in the U.S. Score	TRL Score	Lead Times Score	Replacement Parts Score	Combined Score
AGV	0	0	0 ¹²	0	0	0
Rail-Mounted Gantry Crane	0	0	0 ¹³	0	0	0
Reach Stacker	0	0	100 (TRL7)	0	0	100
Rubber-Tired Gantry Crane	0	0	200 (TRL8)	0	0	200
Shuttle and Straddle Carriers	0	0	0 ¹⁴	0	0	0
Side Handler	0	0	100 (TRL7)	0	0	100
Top Handler	0	0	100 (TRL7)	0	0	100
Yard Truck	0	0	100 (TRL7)	0	0	100

¹² With Gaussin going out of business in December 2024, there is no evidence of development.

¹³ No evidence of development.

¹⁴ No evidence of development.

Table D-12: Commercial Availability Scoring for Hydrogen Fuel Cell Facility Support CHE

Equipment Type	Commercially Available Score	Commercially Available in the U.S. Score	TRL Score	Lead Times Score	Replacement Parts Score	Combined Score
Aerial Lift	300	100	N/A	0	0	400
Cone Vehicle	0	0	0 ¹⁵	0	0	0
Railcar Mover	0	0	0 ¹⁶	0	0	0
Utility Truck, Other	0	0	0 ¹⁷	0	0	0
Utility Truck, Sweeper	300	100	N/A	0	50	450

¹⁵ No evidence of development.

¹⁶ No evidence of development.

¹⁷ Not enough public information to determine TRL.

Operational Feasibility Scoring

Table D-13 through Table D-15 show the Operational Feasibility scoring for battery electric CHE. Table D-16 and Table D-17 show the Operational Feasibility scoring for grid-electric CHE. Table D-18 through Table D-20 show the Operational Feasibility scoring for hydrogen fuel cell CHE.

Table D-13: Operational Feasibility Scoring for Battery-Electric Bulk Material CHE

Equipment Type	Endurance Score	Performance Score	Reliability Score	Logistics Score	Combined Score
Crane, Material Handling	100	0	0	50	150
Crane, Mobile	150	150	0	0	300
Crane, Off-Road	150	0	0	50	200
Dozer	150	0	0	0	150
Excavator	150	150	0	0	300
Forklift, Heavy Lift	150	100	0	50	300
Forklift, Telehandler	150	0	0	0	150
Haul Truck	125	150	100	0	375
Loader or Loader-Excavator	100	0	0	0	100
Log Stacker	0	0	0	0	0

Table D-14: Operational Feasibility Scoring for Battery-Electric Container CHE

Equipment Type	Endurance Score	Performance Score	Reliability Score	Logistics Score	Combined Score
AGV	150	150	150	50	500
Rail-Mounted Gantry Crane	0	0	0	0	0
Reach Stacker	150	0	0	0	150
Rubber-Tired Gantry Crane	0	0	0	0	0
Shuttle and Straddle Carriers	0	0	0	0	0
Side Handler	150	100	0	0	250
Top Handler	150	150	100	50	450
Yard Truck	150	150	100	0	400

Table D-15: Operational Feasibility Scoring for Battery-Electric Facility Support CHE

Equipment Type	Endurance Score	Performance Score	Reliability Score	Logistics Score	Combined Score
Aerial Lift	0	0	0	0	0
Cone Vehicle	0	0	0	0	0
Railcar Mover	0	0	0	0	0
Utility Truck, Other	0	0	0	0	0
Utility Truck, Sweeper	150	0	0	0	150

Table D-16: Operational Feasibility Scoring for Grid-Electric Bulk Material CHE

Equipment Type	Endurance Score	Performance Score	Reliability Score	Logistics Score	Combined Score
Crane, Material Handling	150	0	0	0	150
Crane, Mobile Harbor	150	0	0	0	150
Crane, Off-Road	150	100	0	50	300
Excavator	150	0	0	0	150

Table D-17: Operational Feasibility Scoring for Grid-Electric Container CHE

Equipment Type	Endurance Score	Performance Score	Reliability Score	Logistics Score	Combined Score
Rail-Mounted Gantry Crane	150	150	150	50	500
Rubber-Tired Gantry Crane	150	0	0	0	150
Ship-to-Shore Crane	150	150	150	50	500
Yard Truck	0	0	0	0	0

Table D-18: Operational Feasibility Scoring for Hydrogen Fuel Cell Bulk Material CHE

Equipment Type	Endurance Score	Performance Score	Reliability Score	Logistics Score	Combined Score
Crane, Material Handling	0	0	0	0	0
Crane, Mobile	0	0	0	0	0
Crane, Mobile Harbor	0	0	0	0	0
Crane, Off-Road	0	0	0	0	0
Dozer	0	0	0	0	0
Excavator	0	0	0	0	0
Forklift, Heavy Lift	0	0	0	0	0
Forklift, Telehandler	0	0	0	0	0
Haul Truck	0	0	0	0	0

Equipment Type	Endurance Score	Performance Score	Reliability Score	Logistics Score	Combined Score
Loader or Loader-Excavator	0	0	0	0	0
Log Stacker	0	0	0	0	0

Table D-19: Operational Feasibility Scoring for Hydrogen Fuel Cell Container CHE

Equipment Type	Endurance Score	Performance Score	Reliability Score	Logistics Score	Combined Score
AGV	0	0	0	0	0
Rail-Mounted Gantry Crane	0	0	0	0	0
Reach Stacker	0	0	0	0	0
Rubber-Tired Gantry Crane	150	150	150	50	500
Shuttle and Straddle Carriers	0	0	0	0	0
Side Handler	0	0	0	0	0
Top Handler	0	0	0	0	0
Yard Truck	150	150	0	50	350

Table D-20: Operational Feasibility Scoring for Hydrogen Fuel Cell Facility Support CHE

Equipment Type	Endurance Score	Performance Score	Reliability Score	Logistics Score	Combined Score
Aerial Lift	0	0	0	0	0
Cone Vehicle	0	0	0	0	0
Railcar Mover	0	0	0	0	0
Utility Truck, Other	0	0	0	0	0
Utility Truck, Sweeper	150	150	0	0	300

Technology Readiness Scoring and Grading

Table D-21 through Table D-23 contain the scoring values used to calculate the Technology Readiness Grades for battery-electric CHE. Table D-24 and Table D-25 contain the scoring values used to calculate the Technology Readiness Grades for grid-electric CHE. Table D-26 through CHE TA Appendix D (TRG) Table D-28 contain the scoring values used to calculate the Technology Readiness Grades for hydrogen fuel cell CHE.

Table D-21: Technology Readiness Scoring for Battery-Electric Bulk Material CHE

Equipment Type	Technology Readiness Score (Combined Commercial Availability and Operational Feasibility Scores)	Corresponding Technology Readiness Grade
Crane, Material Handling	550	Demonstration
Crane, Mobile	700	Demonstration
Crane, Off-Road	600	Demonstration
Dozer	450	Demonstration
Excavator	700	Demonstration
Forklift, Heavy Lift	700	Demonstration
Forklift, Telehandler	550	Demonstration
Haul Truck	775	Limited
Loader or Loader-Excavator	500	Demonstration
Log Stacker	0	Development

Table D-22: Technology Readiness Scoring for Battery-Electric Container CHE

Equipment Type	Technology Readiness Score (Combined Commercial Availability and Operational Feasibility Scores)	Corresponding Technology Readiness Grade
AGV	950	Equivalence
Rail-Mounted Gantry Crane	0	Development
Reach Stacker	550	Demonstration
Rubber-Tired Gantry Crane	400	Demonstration
Shuttle and Straddle Carriers	400	Demonstration
Side Handler	650	Demonstration
Top Handler	850	Limited
Yard Truck	850	Limited

Table D-23: Technology Readiness Scoring for Battery-Electric Facility Support CHE

Equipment Type	Technology Readiness Score (Combined Commercial Availability and Operational Feasibility Scores)	Corresponding Technology Readiness Grade
Aerial Lift	400	Demonstration
Cone Vehicle	400	Demonstration
Railcar Mover	400	Demonstration
Utility Truck, Other	400	Demonstration
Utility Truck, Sweeper	550	Demonstration

Table D-24: Technology Readiness Scoring for Grid Electric Bulk Material CHE

Equipment Type	Technology Readiness Score (Combined Commercial Availability and Operational Feasibility Scores)	Corresponding Technology Readiness Grade
Crane, Material Handling	550	Demonstration
Crane, Mobile Harbor	550	Demonstration
Crane, Off-Road	700	Demonstration
Excavator	550	Demonstration

Table D-25: Technology Readiness Scoring for Grid Electric Container CHE

Equipment Type	Technology Readiness Score (Combined Commercial Availability and Operational Feasibility Scores)	Corresponding Technology Readiness Grade
Rail-Mounted Gantry Crane	1000	Equivalence
Rubber-Tired Gantry Crane	550	Demonstration
Ship-to-Shore Crane	1000	Equivalence
Yard Truck	0	Development

Table D-26: Technology Readiness Scoring for Hydrogen Fuel Cell Bulk Material CHE

Equipment Type	Technology Readiness Score (Combined Commercial Availability and Operational Feasibility Scores)	Corresponding Technology Readiness Grade
Crane, Material Handling	0	Development
Crane, Mobile	0	Development
Crane, Mobile Harbor	100	Development
Crane, Off-Road	200	Development
Dozer	0	Development
Excavator	200	Development
Forklift, Heavy Lift	400	Demonstration
Forklift, Telehandler	100	Development
Haul Truck	100	Development
Loader or Loader-Excavator	200	Development
Log Stacker	0	Development

Table D-27: Technology Readiness Scoring for Hydrogen Fuel Cell Container CHE

Equipment Type	Technology Readiness Score (Combined Commercial Availability and Operational Feasibility Scores)	Corresponding Technology Readiness Grade
AGV	0	Development
Rail-Mounted Gantry Crane	0	Development
Reach Stacker	100	Development
Rubber-Tired Gantry Crane	700	Demonstration
Shuttle and Straddle Carriers	0	Development
Side Handler	100	Development
Top Handler	100	Development
Yard Truck	450	Demonstration

CHE TA Appendix D (TRG)Table D-28: Technology Readiness Scoring for Hydrogen Fuel Cell Facility Support CHE

Equipment Type	Technology Readiness Score (Combined Commercial Availability and Operational Feasibility Scores)	Corresponding Technology Readiness Grade
Aerial Lift	400	Demonstration
Cone Vehicle	0	Development
Railcar Mover	0	Development
Utility Truck, Other	0	Development
Utility Truck, Sweeper	750	Limited