The Outlook for Wind Technology Innovation:

What Do the World's Foremost Experts Foresee?

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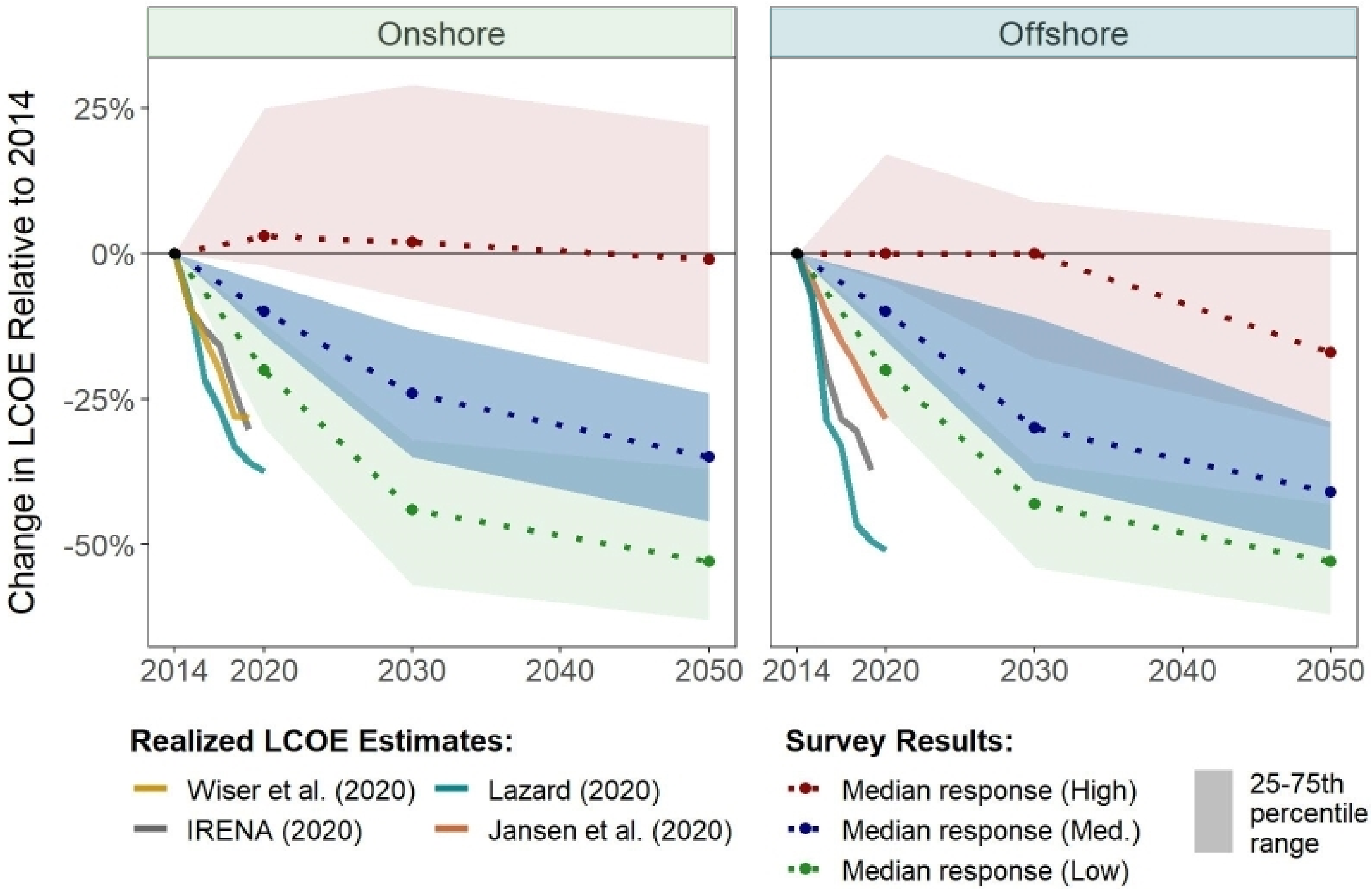
Project Motivation

- Long-term contribution of wind in energy supply depends, in part, on future costs
- Uncertainty about the extent of future cost reduction, technology choices, value options
- Accelerated cost reduction in recent years makes earlier forecasts obsolete

2015 Expert Cost Forecasts vs. Actual Costs



Objectives and scope: conduct expert survey to solicit perspectives on future wind costs *(updating 2015 effort)*

What

Expert survey to gain insight on possible magnitude of future cost reductions, underlying drivers, and anticipated wind technology trends and trade-offs

Covering commercial-scale onshore, and fixed-bottom and floating offshore wind

Who

Among largest energy-technology expert elicitations performed in terms of participants: 140 of world's foremost wind experts

Led by LBNL w/ contributions from NREL and Univ. of Massachusetts, under the auspices of IEA Wind

Why

Inform policy & planning, R&D, industry investment & strategy development; improve treatment of wind in energy-sector models

Complement other tools for evaluating cost reduction: learning curves and engineering assessments

Survey focus is primarily on changes in the levelized cost of energy (LCOE) from 2019 to 2025, 2035 and 2050 under low/median/high scenarios, and on LCOE composition in 2019 and 2035

Summary of survey focus and respondents

Global expert survey on the cost of wind energy, building on earlier survey from 2015

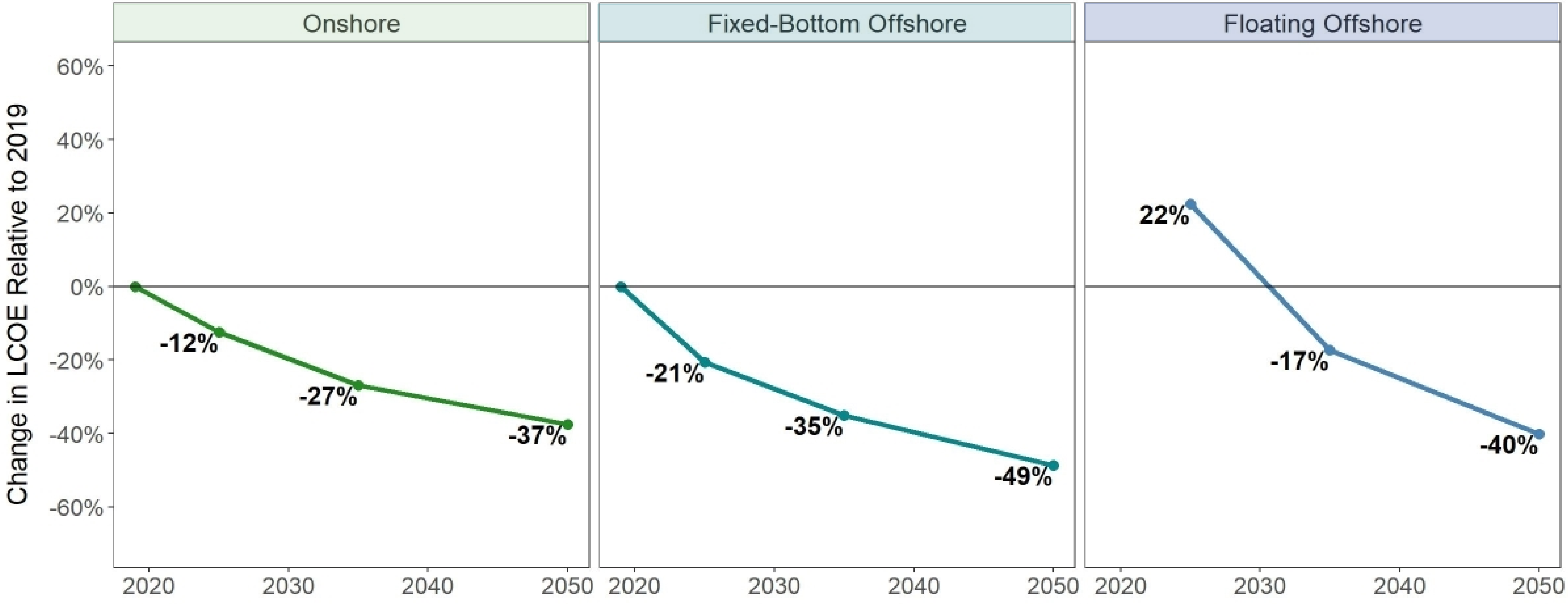
- Includes onshore (land-based) wind as well as fixed-bottom and floating offshore wind
- Focuses on the future levelized cost of wind energy (LCOE), excluding both subsidies and grid interconnection costs outside plant boundary*
- Explores influence of CapEx, OpEx, capacity factor, project life & WACC on LCOE in 2019 & 2035, with additional LCOE estimates for 2025 & 2050
- Investigates median estimates as well as low (10th percentile) and high (90th) cost scenarios
- Elicits site conditions and technology expectations, drivers and constraints
- Additional questions explore options to enhance grid-system value

140 survey participants, dominated by Europe and North America but also Asia

Response Rate			
Survey sample: total			645
Survey respondents: total			140
Response rate: total			22%
Respondents by Wind Application			
Onshore wind			97
Fixed-bottom offshore wind			71
Floating offshore wind			37
Respondents by Organization Type			
Wind power developer, owners, financier, operator, and/or construction contractor			31
Other private-sector company (e.g., consultant)			31
Wind turbine and/or component manufacturer			24
Public research or research management institution			22
University of other degree-granting academic institution			14
Other not-for-profit organization (e.g., NGO, international organizations)			11
Government agency not associated with research management			7
Geographic Region	**Onshore**	**Fixed-Bottom Offshore**	**Floating Offshore**
North America	46	18	5
Europe	39	44	29
Asia	6	5	1
Central & South America	1	0	0
Global Average	3	4	2

* Cost estimates include electrical cabling within the plant, but exclude any needed substations, transmission lines, or grid interconnection costs. For offshore wind, within--plant array cabling is included, but offshore substation, any HVDC collector stations and associated cables, and costs for grid connection to land are all excluded.

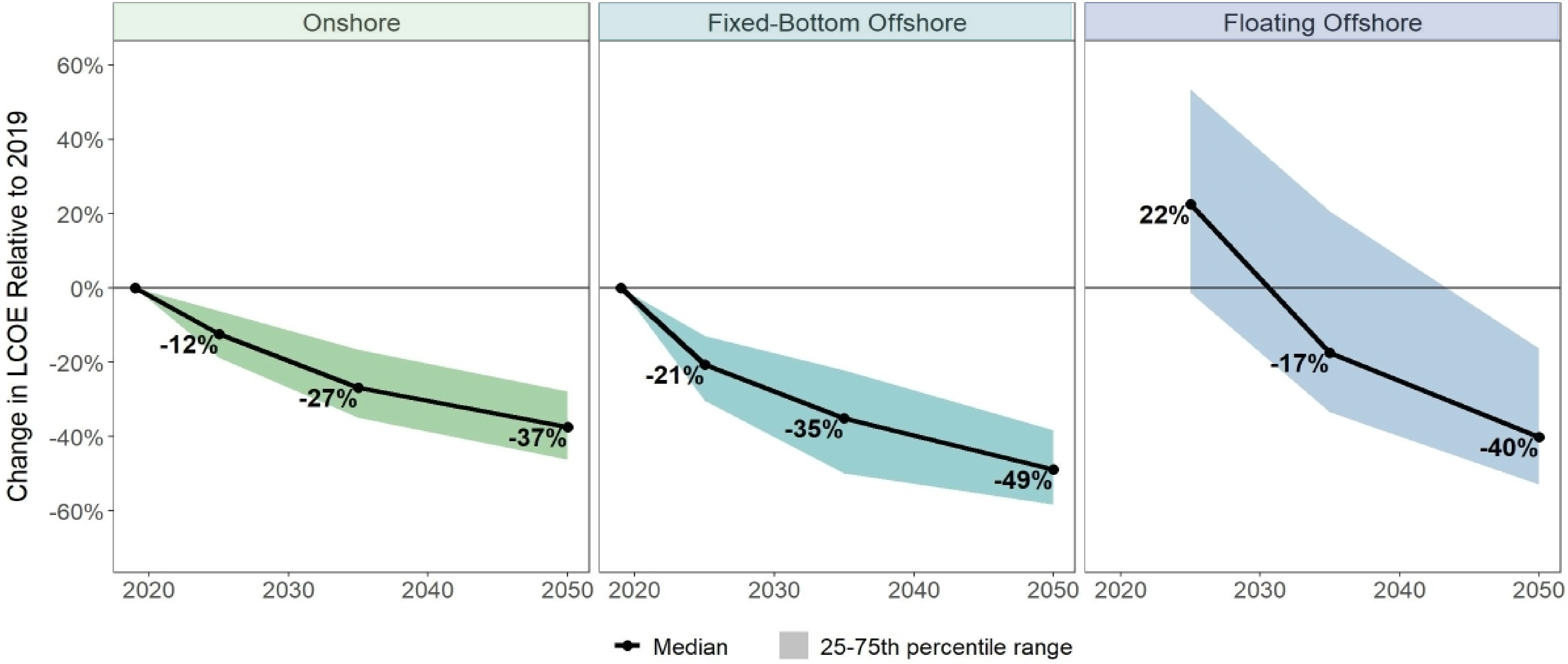
Respondents expect significant LCOE reduction: median "best guess" scenario, median respondent



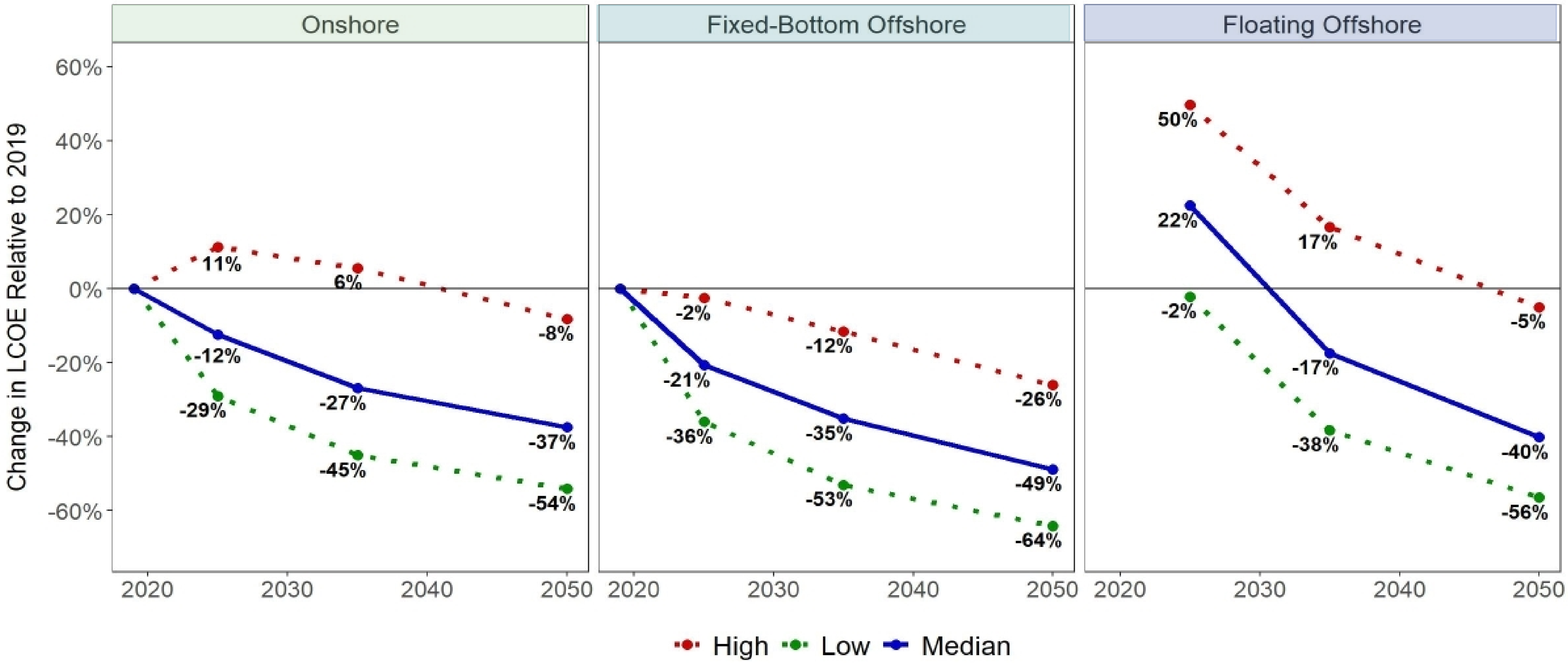
Lines/markers indicate the **median** expert response
For **floating,** change is shown relative to 2019 baseline for fixed-bottom
All dates are based on the year in which a new wind project is commissioned

Pace of cost reduction greatest for floating offshore, then fixed-bottom offshore, then onshore wind

Uncertainty revealed when reviewing range of expert responses: median scenario, 25-75th respondent range



Uncertainty in and sizable opportunity space for LCOE reduction also illustrated by low / high scenario results



Low: Median project cost in 10th percentile of low-cost possible futures
High: Median project cost in 90th percentile of high-cost possible futures

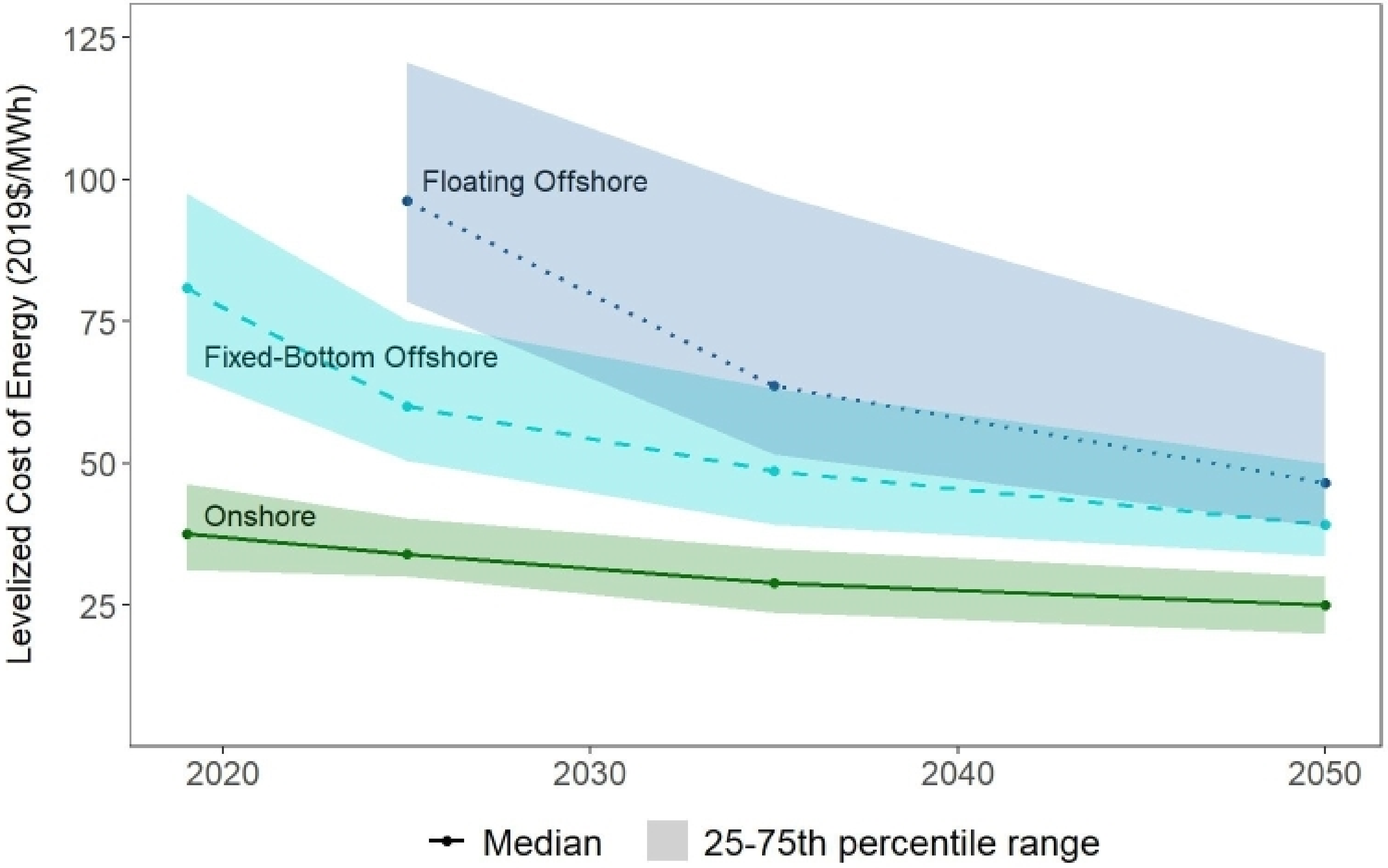
In absolute terms, narrowing gap between onshore & offshore, and fixed-bottom & floating: median scenario

Onshore generally expected to remain lower cost than offshore

LCOE reductions are greater for offshore wind than onshore

LCOE reductions for floating offshore expected to be especially sizable

Greater uncertainty in offshore (especially floating) wind LCOE than in onshore LCOE



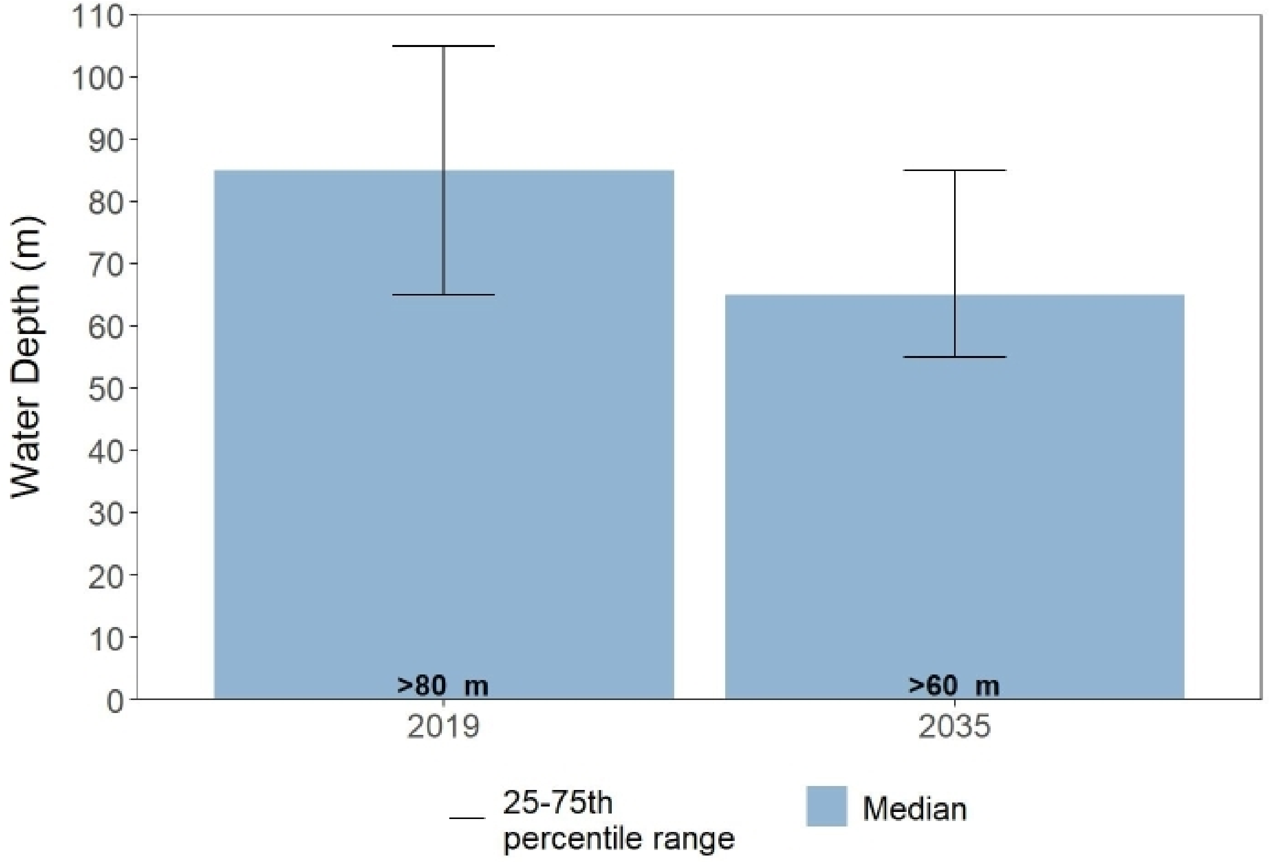
Results assume standardized tax rate (25%), depreciation (20-year straight-line), inflation (2%); exclude interconnection costs outside plant boundary (these interconnection costs tend to be higher for offshore than onshore wind, and should be considered when making overall cost comparisons across wind applications)

Floating foundations are expected to take a growing share of the offshore market

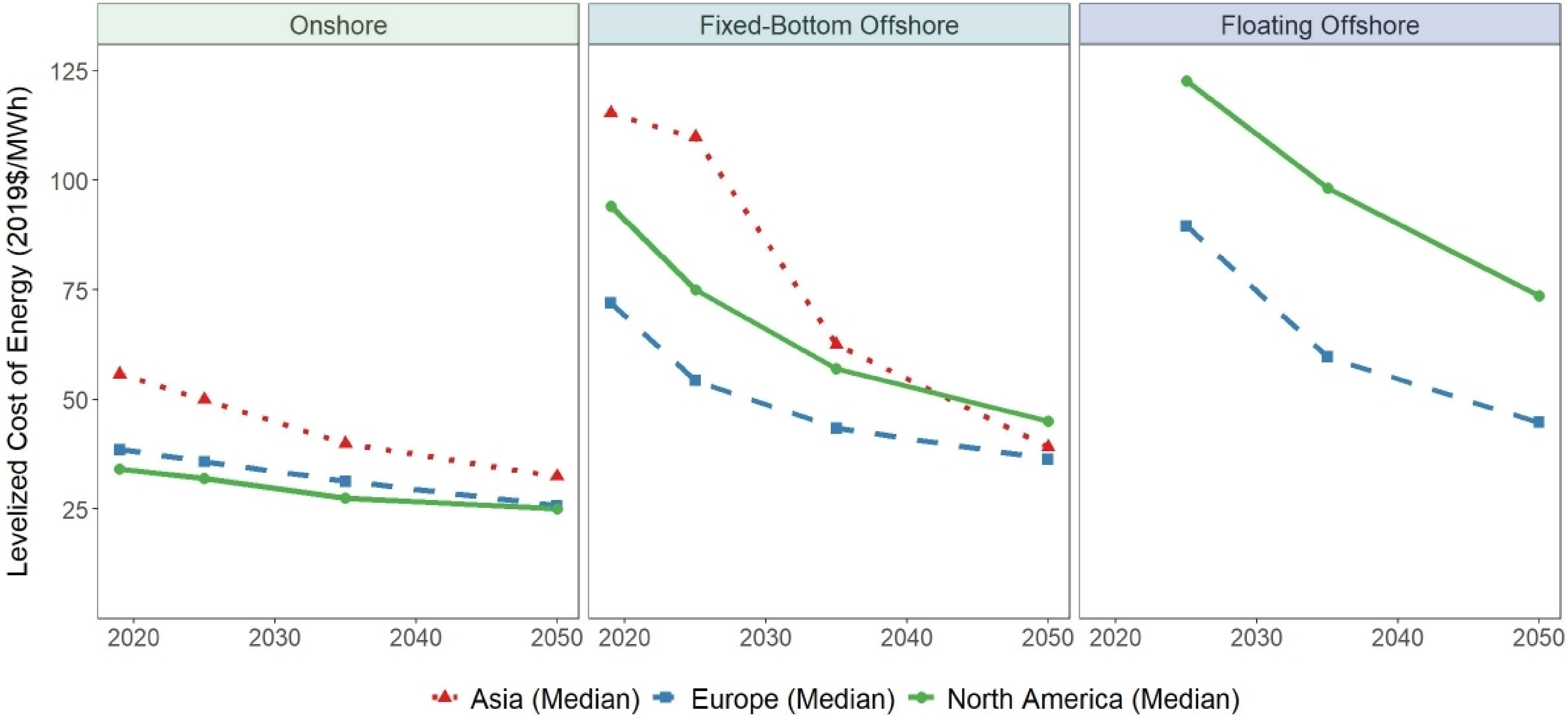
By 2035, the median expert predicts that ***11–25%*** of all new offshore projects globally will feature floating foundations

Developers predict a higher share: median = 26-50%

Water depth at which floating becomes less costly than fixed-bottom expected to decline over time

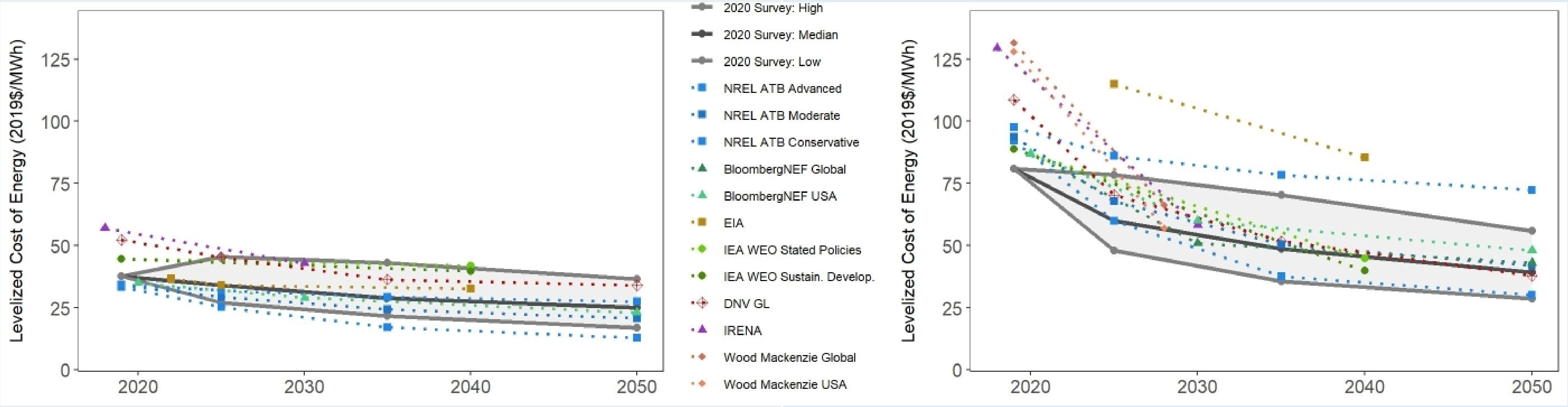


North America expected to host the lowest-cost onshore projects; Europe the lowest-cost offshore

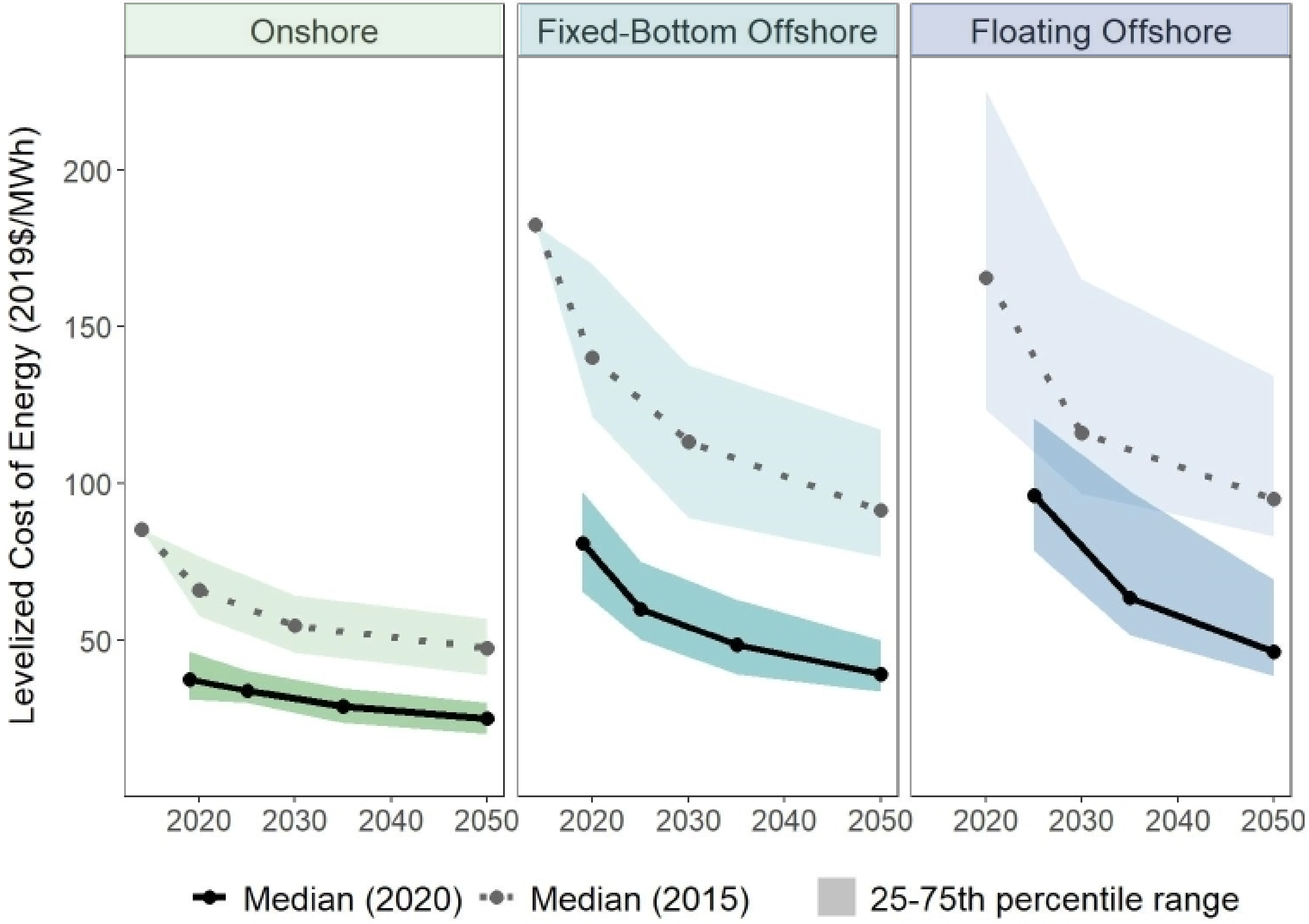


2020 survey results are reasonably consistent with historical learning and many other recent forecasts

Onshore Wind	Offshore Wind
Implicit survey-based LCOE learning rate of ~13%, consistent with long-term trend (10-20%); lower than accelerated learning rate (35-46%) over last 5 years	Implicit survey-based LCOE learning rate of ~14%, towards bottom of range of accelerated learning rate (14-33%) over last 5 years, higher than longer term
Experts more optimistic than IEA , EIA, IRENA, DNV GL and assumptions in integrated assessment models; reasonably consistent with NREL and BloombergNEF	Experts have lower starting point values than many other forecasts, but absolute LCOE estimates are highly consistent by 2030 and beyond; EIA projects higher costs



Expert perspectives about future cost trajectories have fundamentally changed: median scenario, 2020 vs. 2015



Experts in both surveys anticipated LCOE reductions: *similar amount in percentage terms*

Starting baseline values differ dramatically after steep decline in LCOE over last 5 years

Virtually no overlap between the 25th to 75th percentiles of expert estimates across two surveys

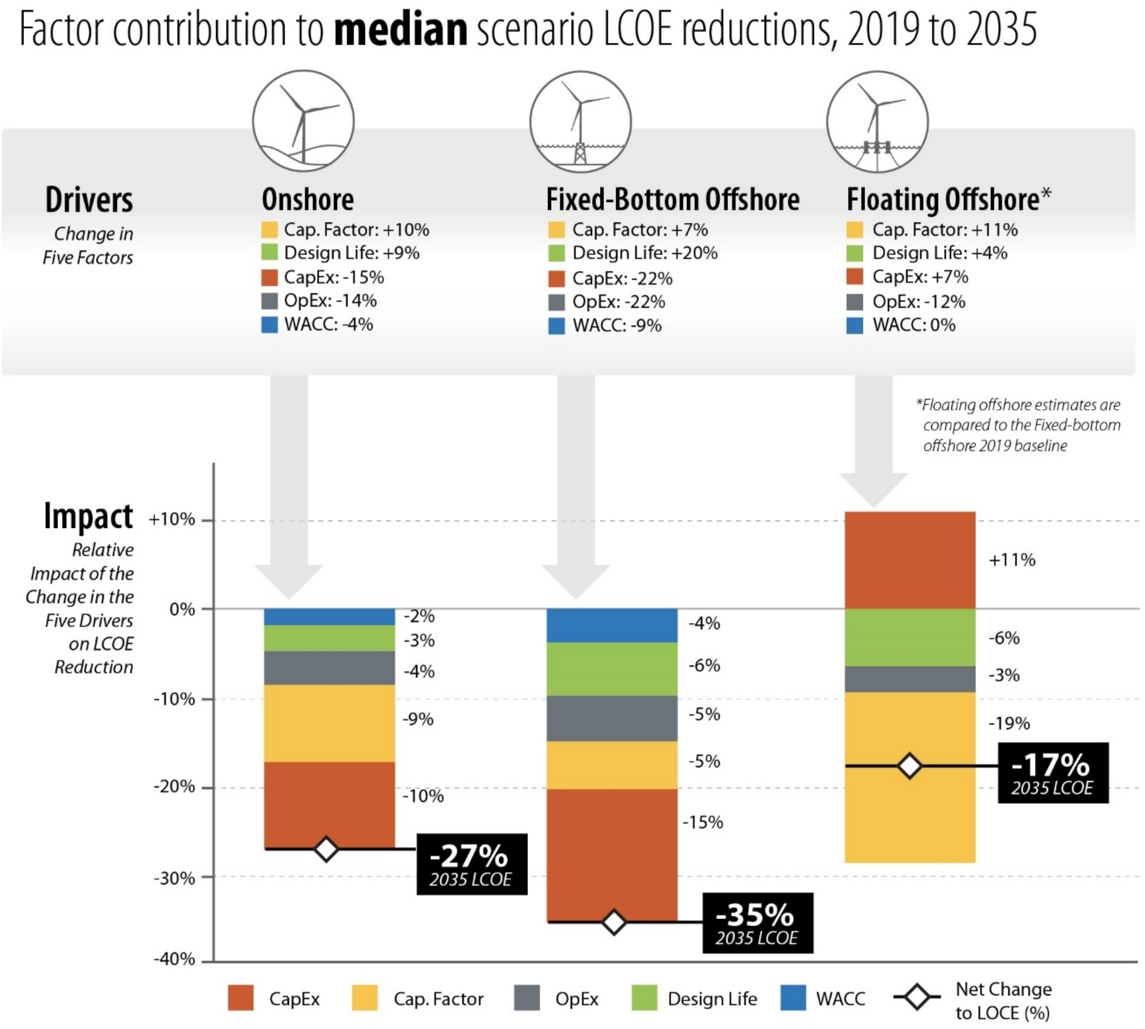
Expected LCOE in 2050 is half what was anticipated in 2015 survey across all applications

LCOE reductions are expected despite a tendency in some respects towards less-attractive wind project sites

Onshore Wind: Average annual wind speed at 100m for newly built projects expected to decline from 7.9 m/s in 2019 to 7.5 m/s in 2035

Typical Offshore Site (newly built in 2035)	**Fixed Bottom** (median)	**Floating** (median)
Distance to Shore	70 km	100 km
Water Depth	42 m	100-199 m
Project Size	900-1299 MW	500-699 MW
Wind Speed (at 100m)	9.5 m/s	10 m/s

How will we get there? Factor contribution to median scenario LCOE reductions, 2019 to 2035

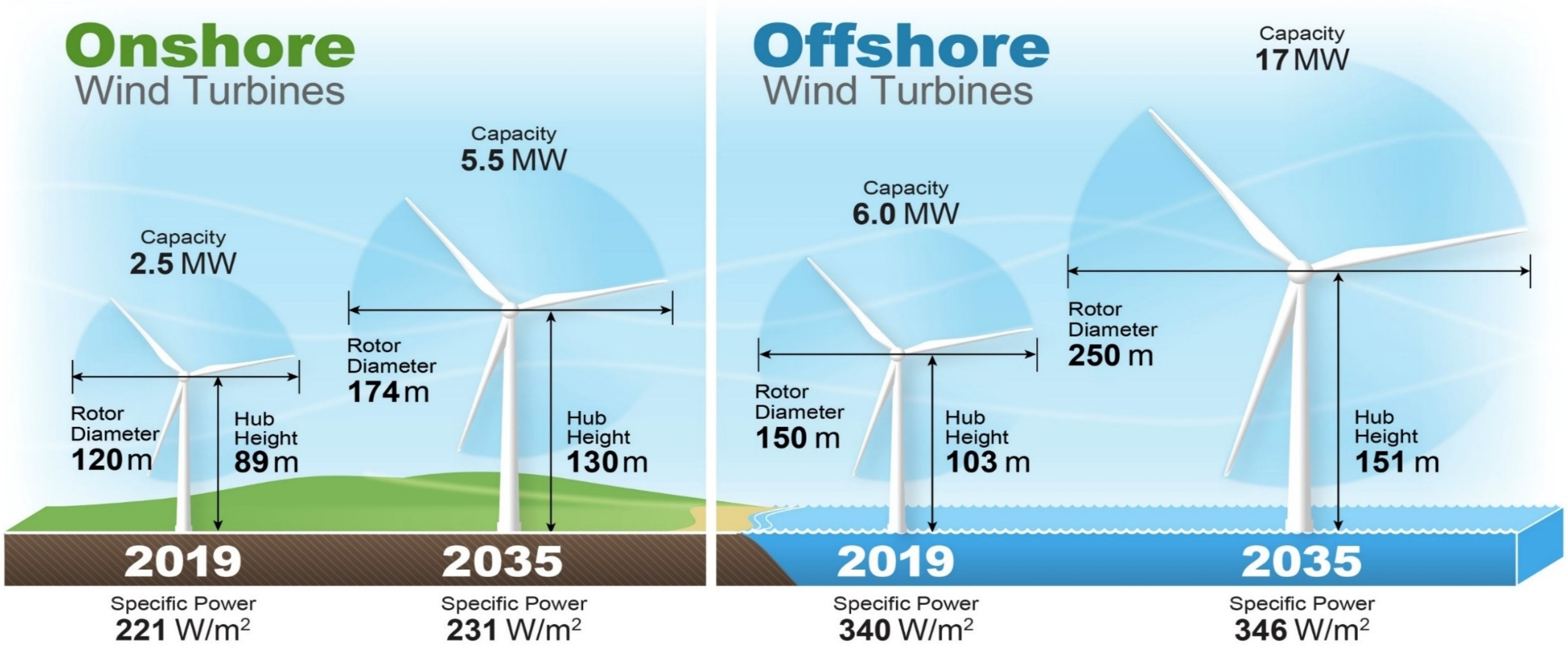


For **onshore wind**, CapEx and capacity factor improvements are most important

For **fixed-bottom offshore**, relative to onshore, capacity factor improvement is less significant, but CapEx and other factors more crucial

Relative to 2019 fixed-bottom baselines, LCOE reductions for **floating offshore** are dominated by enhanced capacity factors; CapEx in 2035 remains higher than 2019 CapEx for fixed-bottom

LCOE improvements driven in part by growth in turbine size: median expected turbine size in 2035 (vs. 2019)



For offshore, 2035 estimates are compared to a global 2019 median; for onshore, a 2019 U.S. median is shown

Relatively modest differences by region: Onshore: lower specific power (and larger rotors) and lower hub height in North America than in Europe. Offshore: somewhat higher capacity ratings in Europe. **Leading experts** predict larger turbines and lower specific power. For onshore, **manufacturers** predict lower specific power and higher hub heights than **developers**. For offshore, **manufacturers** and **developers** predict larger turbines than other respondents.

Constraints to continued increases in turbine size are diverse, and differ between onshore and offshore wind

Onshore wind: factors that may limit future growth in turbine size	No impact (0) ↔ Large impact (3)
Permitting: Siting and permitting regulations and requirements	2.4
Transportation: Transportation limitations and costs	2.4
Community: Local community concerns	2.2
Design/materials: Design and materials constraints, leading to high costs	1.8
Cranes: Lifting / crane capabilities and costs	1.8
Risk: Increased risk given larger impact associated with failure of single turbine	1.1

Offshore wind: factors that may limit future growth in turbine size	No impact (0) ↔ Large impact (3)
Vessels: Vessel capabilities and costs	2.3
Cranes: Lifting / crane capabilities and costs	2.2
Ports: Port capabilities and costs	2.2
Design/materials: Design and materials constraints, leading to high costs	1.9
Permitting: Siting and permitting regulations and requirements	1.8
Transportation: Transportation (e.g., bridge clearances) limitations and costs	1.5
Community: Local community concerns	1.3
Risk: Increased risk given larger impact associated with failure of single turbine	1.2

Beyond LCOE: wind plant design and operation will be impacted by options to enhance grid-system value

Onshore wind: frequency of use of grid-value enhancement options in 2035	Widespread use: *over 50% of projects*	Significant use: *over 10% of projects*
Large rotors: Employing larger rotors and/or taller towers to increase production when wholesale prices are higher	77%	95%
Storage hybrids: Co-locating wind projects with storage at the plant site or point of interconnection	46%	83%
Curtailment: Self-curtailment when wholesale prices are low or negative to avoid financial losses during those times	45%	79%
Life extension: Operating to reduce mechanical stress when wholesale prices are low, in part to extend project life	38%	71%
Interconnection: Interconnecting projects to locations with higher wholesale prices and/or lower levels of curtailment	30%	70%
Balancing services: Using wind plants to provide balancing reserves and/or other essential reliability services	29%	81%
Generator hybrids: Co-locating wind projects with other generating sources at the plant site or point of interconnection	26%	80%
Hydrogen: Using wind energy to produce fuels, such as hydrogen, at the plant site or point of interconnection	22%	56%
Overplanting: Building more wind power capacity than transmission interconnection capacity	17%	65%

Offshore wind: frequency of use of grid-value enhancement options in 2035	Widespread use: *over 50% of projects*	Significant use: *over 10% of projects*
Large rotors: Employing larger rotors and/or taller towers to increase production when wholesale prices are higher	43%	78%
Balancing services: Using wind plants to provide balancing reserves and/or other essential reliability services	35%	87%
Interconnection: Interconnecting projects to locations with higher wholesale prices and/or lower levels of curtailment	30%	75%
Curtailment: Self-curtailment when wholesale prices are low or negative to avoid financial losses during those times	28%	56%
Storage hybrids: Co-locating wind projects with storage at the plant site or point of interconnection	26%	70%
Life extension: Operating to reduce mechanical stress when wholesale prices are low, in part to extend project life	26%	58%
Hydrogen: Using wind energy to produce fuels, such as hydrogen, at the plant site or point of interconnection	23%	73%
Overplanting: Building more wind power capacity than transmission interconnection capacity	21%	44%
Generator hybrids: Co-locating wind projects with other generating sources at the plant site or point of interconnection	11%	30%

Key findings

1. Wind energy has experienced accelerated cost reduction over the last five years, making previous cost forecasts obsolete
2. Experts in 2020 anticipate future onshore and offshore wind costs that are approximately 50% lower than predicted in 2015
3. These reductions will be shaped by not only CapEx, but also capacity factor, OpEx, project life, and cost of finance
4. If realized, this will allow wind to play a more substantial role in global energy supply and energy-sector decarbonization than previously anticipated
5. Uncertainties in the magnitude of cost reduction are significant, illustrating the importance of uncertainty in modeling and in policy, planning, investment, & research decisions
6. As costs decline, additional focus may turn to the value of wind in energy markets, and to the many barriers that hinder deployment

Acknowledgements

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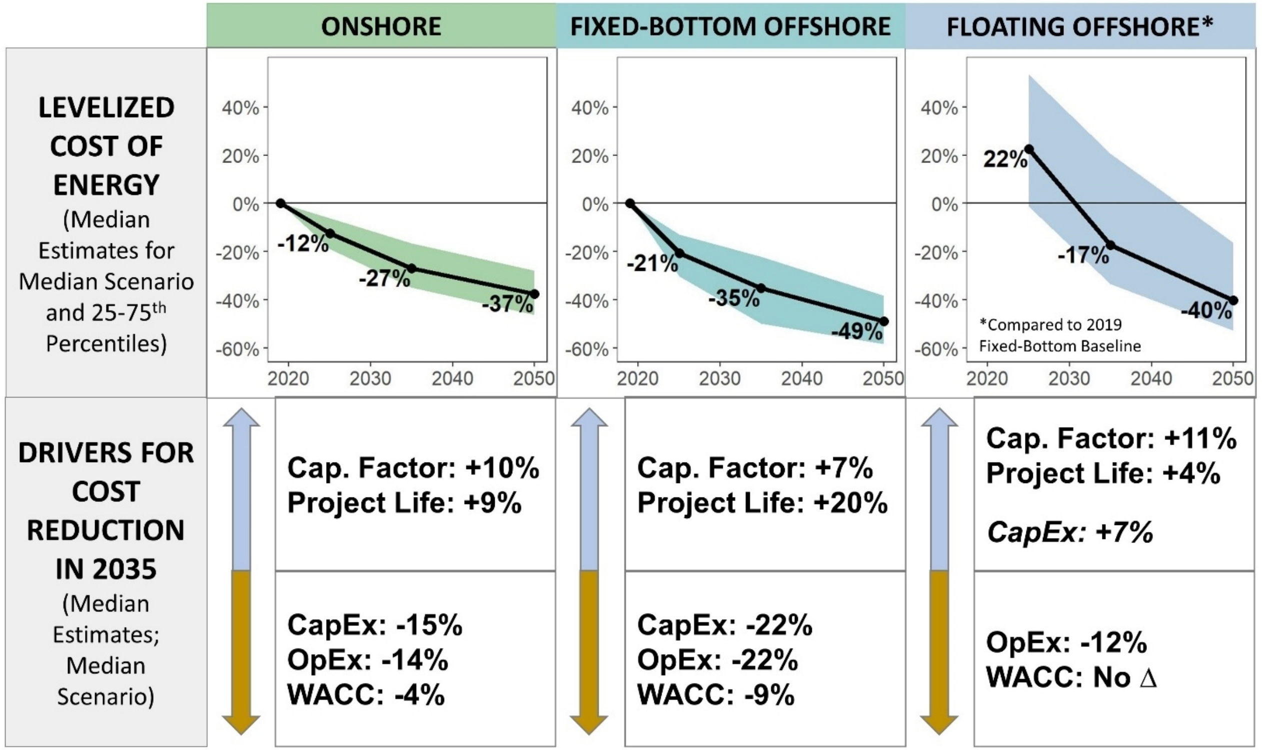

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